FISHNISH B, SOUND OF MULL

Bath Medicine Dispersion Report

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1 Executive Summary

This report describes simulations of bath treatment releases based on the outputs of a hydrodynamic model which was developed for the Loch Linnhe area. The aim of the investigation was to understand whether the consented level of Azamethiphos for bath treatment at Scottish Sea Farms Ltd.'s Fishnish B site (details in Table 1.1) could be safely increased while maintaining satisfaction of SEPA Maximum Allowable Concentration (MAC) and Environmental Quality Standard (EQS) criteria.

A range of different treatment scenarios were investigated, in addition to sensitivity to horizontal dispersion (observed to be greater than the default SEPA value in the locality of the site) and release time/tide state.

Simulations indicated that the existing consented medicine mass of 476.4 g could be safely increased. The results in this report provide two main findings:

1. Running individual releases at 750 g/pen meets the required standard at 3 hr post release. This means that the 3 hr limit should be set at 750 g (Section 4.3).
2. Running a realistic treatment scenario (7 pens over 4 days - releases at 0, 6, 24, 30, 48, 54, 72 hours from first release, 375 g/pen) meets the required standards at 72 hr post treatment scenario end. This means that the 24 hr limit should be set at 750 g (Section 4.4-4.6).

The 3 hr and 24 hr limits for Azamethiphos are therefore recommended to be set at 750 g.

Table 1.1 Summary of site details and model results.

Site details	
Site Name	Fishnish B
Locality	Sound of Mull
Pen centre (OSGB easting/northing, m)	165202, 742797
Consented biomass (T)	975 (proposed increase to 1300 T)
Configuration	
Number of pens (configuration)	7 (50 m grid, 1 x 7)
Pen size	100 m circumference
Pen group distance to shore	255 m (centre)
Net depth (m)	13 m
Pen grid orientation	288^{o}
Depth (m)	31 m
Bath medicines	
Current consent (24 hr)	476.4 g
Recommended consent (3 hr)	750 g
Recommended consent (24 hr)	750 g

2 Introduction

This report has been prepared by Scottish Sea Farms Ltd. to meet the requirements of the Scottish Environmental Protection Agency (SEPA) for an application to adjust the consent for topical sea lice medicines at the Fishnish B site (OSGB 165202, 742797; Figure 2.1).

The report describes the application of coupled hydrodynamic and particle tracking models to estimate the spread of bath medicines following treatment events, and to evaluate quantities of medicine which may be used in compliance with SEPA Environmental Quality Standards.

The modelling procedure follows the current version SEPA marine modelling guidance as available at November 2022, as far as possible.

The site configuration is composed of 7 x 100 m pens on a 50 m grid, with centre-point of cage grid at (165202, 742797) m (OSGB Easting/Northing). Key data relating to the site are summarised in Table 1.1.

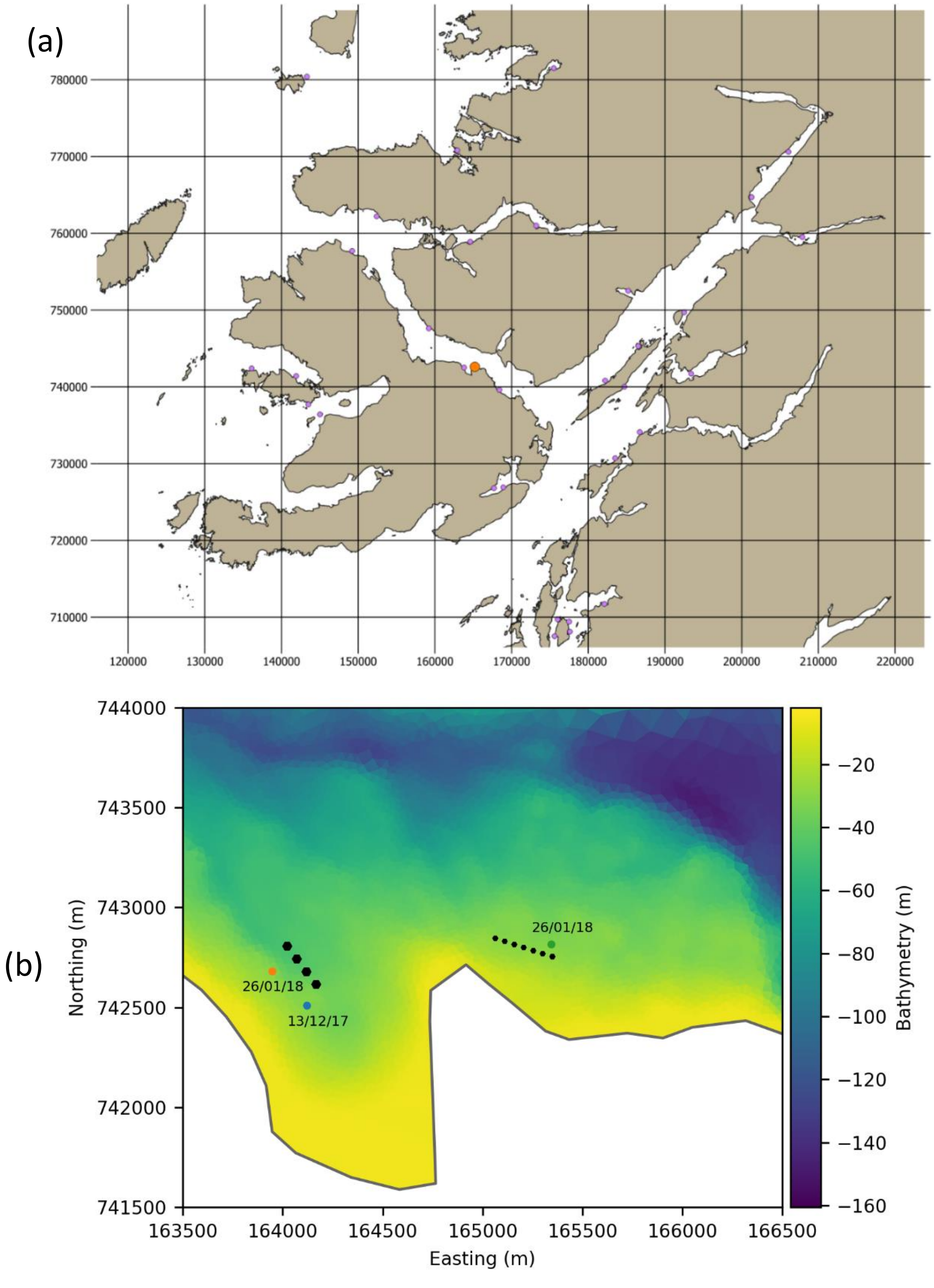

Figure 2.1 Map of site (a) showing broad location on west coast on Scotland (Fishnish B site: orange disc; other salmon farms: mauve discs) and (b) showing close view of Fishnish Point, pen and current meter locations used in this study, Sound of Mull. The western pen group is Fishnish A site (not included in the simulations presented here), and the eastern pen group is Fishnish B site.

3 Methodology

3.1 Hydrodynamic and particle tracking models

The hydrodynamic model used in this work was the DHI MIKE 3 numerical modelling system, which has been developed for general simulation of water flows in estuaries, bays and coastal areas, in addition to wider ocean domains. MIKE 3 is a three-dimensional model which can account for density variation, currents and tidal elevation (Danish Hydraulic Insitute 2017a).

MIKE 3 is a finite volume hydrodynamic model, using an unstructured spatial mesh formulation which allows representation of fine scale features in coastline and bathymetry while retaining computational efficiency through a coarser mesh in simpler areas. Horizontal elements in the model can be triangular or quadrilateral; the model described here used exclusively triangular elements. This approach is particularly important for complex coastal regions such as the Scottish west coast. A similar method is used by other current hydrodynamic models such as FVCOM (Chen et al. 2013). This allows simulation of spatial domains that were not possible with earlier regular-grid models such as POLCOMS and ROMS, which were developed with wider ocean regions in mind.

The model proceeds by solving the 3D shallow water equations (incorporating the hydrostatic assumption) on the provided spatial mesh, using a discrete timestep which is governed by the finest horizontal mesh resolution and the depth of the water at that location; the Courant-Friedrich-Lévy (CFL) condition. Simulation is also possible using the 3D Navier-Stokes equations, which omits the hydrostatic assumption but increases simulation time and complexity.

For all simulations, an initial spin-up period of at least 9 days was used in order to allow currents, temperature and salinity to reach an appropriate state prior to any period of output used for subsequent analysis or particle tracking.

Particle tracking was also carried out using the DHI MIKE software suite. Flow fields (U/V/W velocities) generated by MIKE 3 were used to drive the movement of passive particles (no active horizontal or vertical movement) in the water column. Particles were subject to advection due to currents, horizontal and vertical diffusion (described by a random walk formulation) at fixed rates. Each particle was assigned to represent a specific mass of medicine at the moment it was released (equal to total treatment mass, divided by the number of particles per release). This mass weighting is considered to decline exponentially over time at a fixed rate governed by the chemical half-life prescribed by SEPA. Presently the SEPA default value of half-life for Azamethiphos is 5.6 days; this was reduced from the previous value of 8.9 days in light of the latest evidence (Veterinary Medicines Directorate 2020).

3.2 Model domain and boundary conditions

The model domain used for this study covers the region encompassing Loch Linnhe, Sound of Mull and Loch Sunart (Figure 3.1). It consists of 30048 node points, and 56018 triangular elements, which vary in size from 216 - 45,141 m^2, with refinement in the locality of the SSF Fishnish and nearby Fiunary sites (Figure 3.2). The maximum depth within the domain is 198 m.

Within a 2 km square centred on Fishnish B site location (OSGB36 E: 164121, N: 742510), element area has a median value of 643 m^2 (slightly smaller than a default NewDepomod square grid element; 5^{th} %-ile = 425 m^2, 95^{th} %-ile = 980 m^2), and element side length has a median of 40.0 m (5^{th} %-ile = 32.7 m, 95^{th} %-ile = 50.0 m).

Model domains were developed using the MIKE Mesh Generator tool (Danish Hydraulic Insitute 2017b), with additional data processing carried out using QGIS 3.22, Python 3.10, and R 4.1.0/RStudio

1.4.1106. Coastline data was obtained from Ordnance Survey OpenData (Ordnance Survey 2021). Coastline arcs were validated, smoothed and subsampled at 50 m resolution using QGIS 3.14, and imported into MIKE using the shp2xyz tool before manual work on coastline detail for the desired model resolution. Minor islands were removed, in accordance with standard practices. Background bathymetry data for the region were obtained from the Scottish Shelf Model Wider Loch Linnhe System submodel mesh (Price et al. 2016). Finer resolution (2-8 m horizontal grid) multibeam bathymetry data for the Sound of Mull were obtained from UK Hydrographic Office Marine Data Portal (UKHO 2021). The hydrodynamic model meshes were generated in the MIKE mesh generator, using the automated generation and smoothing routines. Meshes were manually refined along the coastline to i) ensure elimination of elements with two land edges; ii) ensure that narrow channels were represented by at least three elements laterally (in exceptional cases of minor channels, two elements); and iii) ensure that unrealistic steps in shoreline bathymetry were not introduced by the combined bathymetry data sources.

Generated meshes were checked in respect of estimated CFL number, and optimised to eliminate elements which would enforce a very short time step (in particular, combining or increasing the size of elements which were horizontally small but in deep water).

The domain includes 16 freshwater sources, representing the major river inputs (Appendix A1; Figure F1). 5 of these rivers are gauged (or composed of gauged rivers); discharge volume for ungauged catchments was estimated by applying an area scaling to the discharge of the nearest gauged river (Appendix A1; Figure F2, Table T1). Temperature of river inputs was assumed to be equal between rivers, but vary according to the monthly mean of values recorded for the River Aline as part of the Scottish River Temperature Monitoring Network (Appendix A1; Figure F3).

The model domain has two open boundaries, one linking the western tip of the Ardnamurchan peninsula with the north of Mull, and the other linking the south coast of Mull with the island of Seil. Forcing at these boundaries was provided in the form of time-series transects of surface elevation, U/V water velocities (varying over depth) and temperature and salinity (also varying with depth). Values were extracted from the Scottish Association for Marine Science (SAMS) “WeStCOMS” FVCOM hindcast implementation for the Scottish west coast (Aleynik 2020) at 1 hour temporal resolution, and interpolated onto the model boundary nodes. Initial conditions for model simulations were also derived from WeStCOMS, with surface elevation (2D field), temperature and salinity (3D fields) for the specified model start times. In accordance with standard practices and SEPA guidance, model velocities were initiated at zero and allowed to go through a “spin-up” period of 9 days prior to being used for calibration, validation or particle tracking applications.

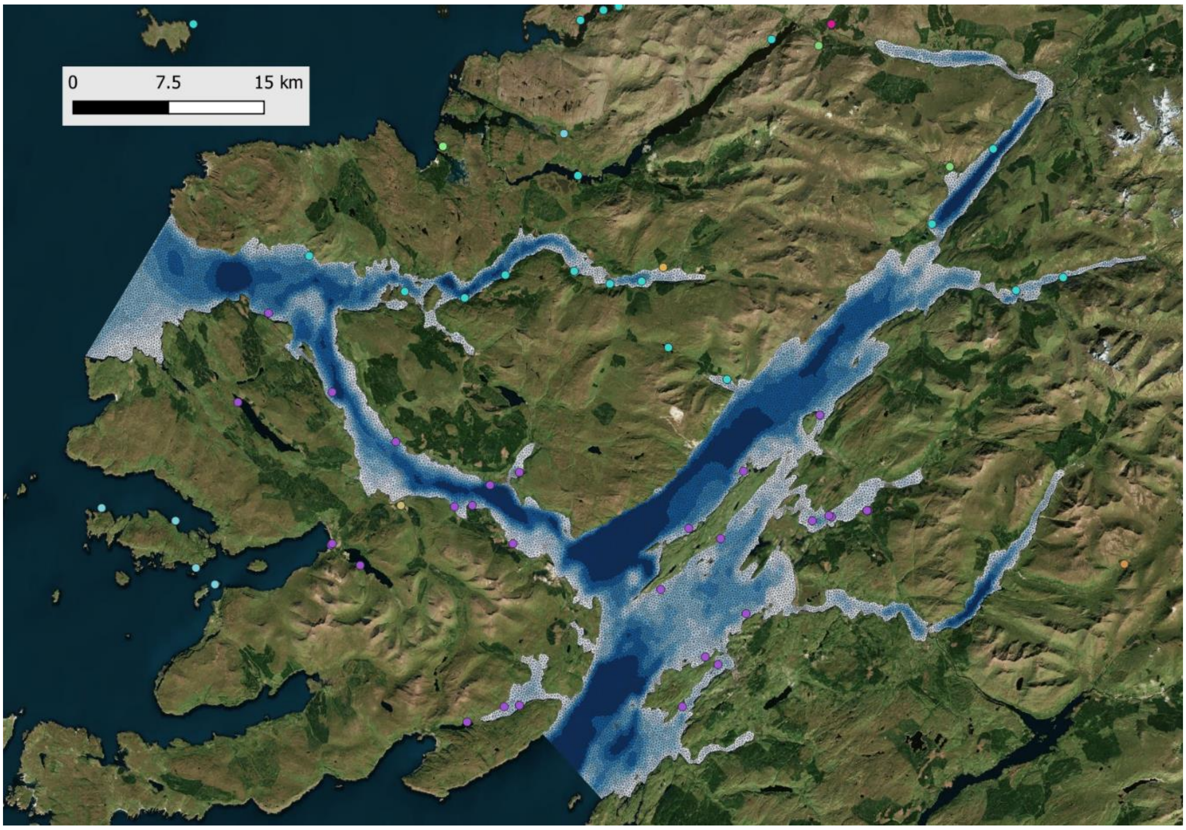

Figure 3.1 Model domain, covering the Sound of Mull, Loch Linnhe and Loch Sunart.

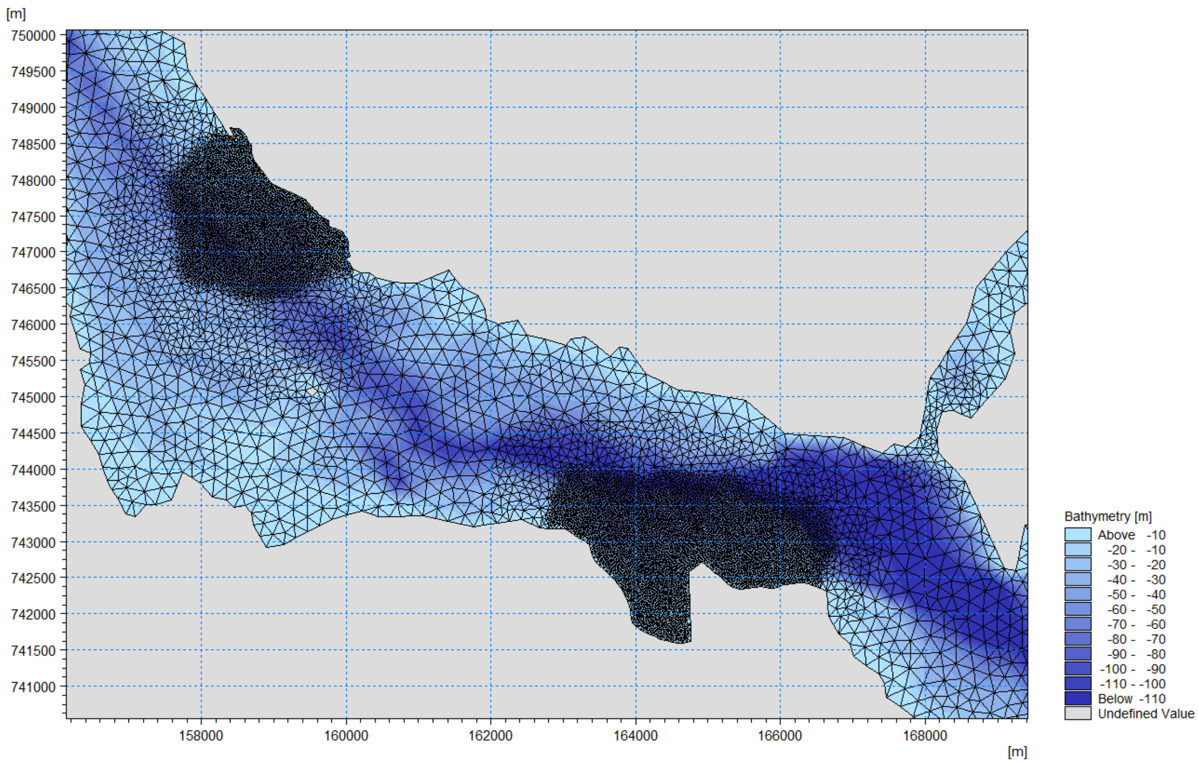

Figure 3.2 Cropped view of model mesh in the neighbourhood of Fishnish (lower highly resolved area) and nearby Fiunary (upper left highly resolved area) sites.

3.2.1 Model calibration/validation

The hydrodynamic model calibration was carried out using a current meter record collected at the nearby Fishnish A site (around 1 km away from the focal Fishnish B site) over two periods:

- *DPL1Y000*: 13/12/2017-12/01/2018 (30 days)

Validation of the hydrodynamic model outputs was then made against meter records collected at the two Fishnish sites:

- *DPL1X000*: 26/01/2018-13/03/2018 (Fishnish A; 45 days)
- *FishB20180126T122904*: 26/01/2018-03/03/2018 (Fishnish B; 36 days)

These meter locations are indicated in Figure 2.1.

Bed roughness length scale and wind friction were used as primary tuning parameters. Previous work (unpublished) calibrating a hydrodynamic model at the nearby Fiunary site in the Sound of Mull indicated that a bed roughness length of 0.01 m (matching experimental studies in the locality, and reflective of the relatively smooth muddy seabed; Adams et al. 2020) provided the best match with observational data, and this value was therefore used as a starting point.

Hydrodynamic model calibration and validation results are described in detail in Appendix A2 and A3 respectively.

Table 3.1 Current meter data used for model calibration/validation.

	Record 1 (DPL1Y000)	**Record 2 (DPL1X000)**	**Record 3 (FishB20180126T122904)**
Position (OSGB m)	164121, 742510	163946, 742683	165343, 742817
Depth at location (Chart Datum) (m)	28.7	27.6	28.56
Surface bin height above bed (m)	24.7	22.7	23.81
Pen-bottom bin height above bed (m)	16.7	14.7	18.81
Bottom bin height above bed (m)	2.7	2.7	2.81
Start time	13/12/2017	26/01/2018	26/01/2018
End time	12/01/2018	13/03/2018	03/03/2018
Duration (days)	30	45	36
Interval (minutes)	20	20	20
Purpose	Calibration	Validation	Validation

3.3 Medicine dispersion modelling

3.3.1 Approach

For particle tracking simulations, two release (treatment start) times were selected from the hydrodynamic model output:

- 29/01/2018 (release during SPRING tide)
- 07/02/2018 (release during NEAP tide)

Releases on these dates, and the corresponding periods over which particle dispersal would be assessed, are shown in Figure 3.3 (for an example treatment starting 24 hours prior to the treatment completion time).

Sensitivity to specific release time for neap and spring period dispersal was estimated by adjustment to the particle tracking simulation start time of +/- 6 hrs about the baseline value.

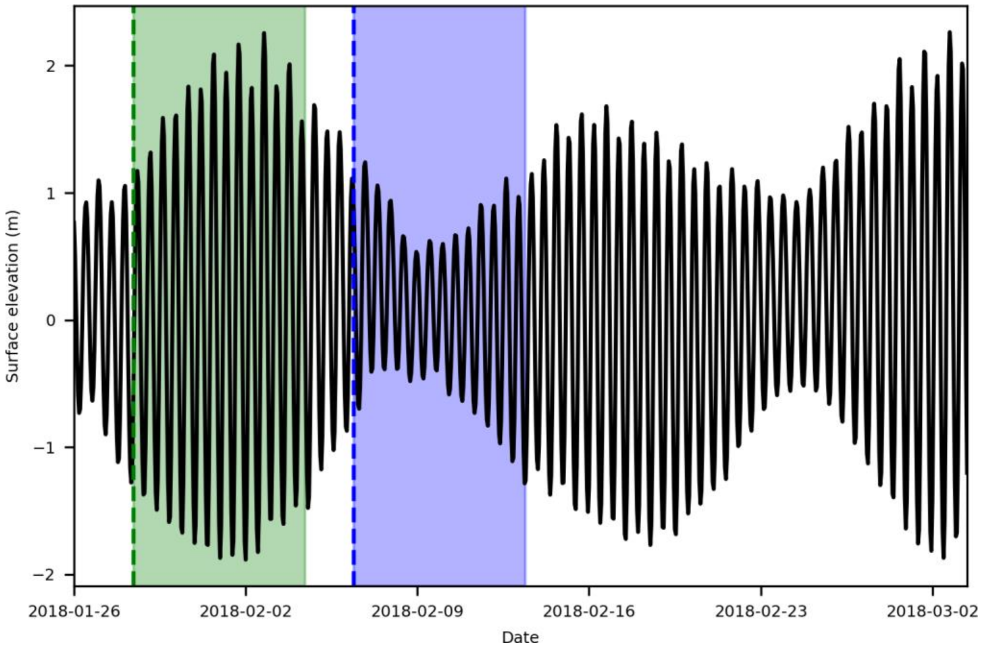

Figure 3.3 Surface elevation at Fishnish B site. Particle dispersal period over spring tide is indicated in green, and dispersal over neap tide is shown in blue.

A scenario for particle release was defined in order to simulate a realistic schedule for treatment at the site. In this scenario, 2 pens were treated on three consecutive days, with a 6 hour interval, and a final treatment being carried out on the fourth day (releases at 0, 6, 24, 30, 48, 54, 72 hours from first release).

Bath treatment events were simulated using a release of 100,000 model particles per pen treated, with each particle representing an equal proportion of the total treatment mass (total 700,000 particles per simulation). Particles were released randomly within a pen's lateral area and over the top 3 m of the water column. **The initial treatment mass (derived as the 3 hr limit from BathAuto) was taken to be 997.4 g (Appendix A5).**

Simulated particles were passive, neutrally buoyant, and subject to both horizontal and vertical advection (derived from hydrodynamic model flow fields) and dispersion (set to fixed constant values; by default 0.1 $m^2 s^{-1}$ horizontally and 0.001 $m^2 s^{-1}$ vertically). As per present SEPA guidance, half-life for particles was set to 5.6 days (via a mass decay rate of $1.43 \times 10^{-6} s^{-1}$).

Dispersion studies close to the farm location have identified that dispersion is potentially higher at Fishnish A site than the default parameter values suggested in the SEPA guidance (Anderson 2011) (see Section 3.4 in this report). Sensitivity to horizontal dispersion was tested with additional simulations using horizontal dispersion coefficients of 0.05, and 0.5 $m^2 s^{-1}$.

The set of dispersion simulations carried out is summarised in Table 3.2.

Table 3.2 Summary of dispersion simulation parameters for sensitivity testing in the main set of runs.

ID	Tide	Dispersion	Timing adjustment (hr)
1	Neap	0.1	0
2	Neap	0.1	-6
3	Neap	0.1	+6
4	Neap	0.1	0
5	Neap	0.05	0
6	Neap	0.5	0
7	Spring	0.1	0
8	Spring	0.1	-6
9	Spring	0.1	+6
10	Neap	0.1	0
11	Neap	0.05	0
12	Neap	0.5	0

3.3.2 Mass limit assessment

Simulations using the BathAuto 3 hr compliant mass of 997.4 g per pen release were consistently compliant with the 3 hr and 72 hr EQS criteria. However, the 72 hr MAC threshold was breached by a large number of sensitivity runs at this treatment mass, and so an investigation into medicine masses which did not breach this threshold was carried out.

Adjustments to the total mass released per treatment in conjunction with assessment of compliance with Maximum Allowable Concentration (MAC) and Environmental Quality Standard (EQS) criteria. This allowed determination of:

- A recommended maximum mass for release within a 3 hr window. For this purpose a range of increased treatment masses were applied to the most conservative run, defined to be the individual pen release closest to 3 hr EQS threshold, of all individual pen releases (4 per scenario/parameter set) within the main sensitivity set of runs.
- A recommended maximum mass for release within a 24 hr window. For this purpose a range of increased treatment masses were applied to the most conservative run, defined to be that closest to 72 hr MAC or EQS threshold, of those within the main sensitivity set of runs.

3.3.3 Output statistics

Output statistics were generated for all particle dispersion simulations in accordance with the current version of SEPA guidance (dated 16th September 2022). The following values were calculated, based on concentrations within the top 3 m of the water column, as per SEPA guidelines:

- Timeseries of area > 3 hr EQS (threshold 250 ng l^{-1})
- Timeseries of area > 72 hr EQS (threshold 40 ng l^{-1})
- Timeseries of maximum concentration vs 72 hr MAC (threshold 100 ng l^{-1})

The 3 hr EQS area was derived from the calculated BathAuto ellipse at that time (Appendix A5), as per present SEPA guidance. Plots of medicine mass distribution at the specific EQS times were generated.

3.4 Dispersion study

A study was previously carried out at Fishnish pier (located around 800 m WNW of the Fishnish A site location) in order to assess the likely fate of materials released during construction of the pier facility (Anderson 2011). The study details two releases, each of 6 GPS drifting buoys which reported their location every 30 seconds. These locations were used to derive horizontal dispersion coefficients in Fishnish Bay.

During the first release, drifters were transported eastwards towards the site location, and found dispersion coefficient values of k_x=0.789 and k_y=0.320 m^2 s^{-1} (that is, differing depending on the directional axis considered), which were considered to be indicative of turbulent conditions and tidal flows. During the second deployment, drifters ultimately moved into the main channel of the Sound, and demonstrated a very high level of separation k_x=14.798 and k_y=0.460 m^2 s^{-1}, experiencing current speeds up to 0.50 m s^{-1}. Both releases indicated a significant shoreline eddy under both ebb and flood.

The dispersion coefficients estimated here are higher that the default values typically recommended by SEPA, and sensitivity of model results to this parameter is therefore demonstrated.

4 Results

4.1 Initial simulations (baseline BathAuto mass)

Simulations using the BathAuto 3 hr compliant mass of 997.4 g per pen release were consistently compliant with the 3 hr and 72 hr EQS criteria. However, the 72 hr MAC threshold was breached by a large number of sensitivity runs at this treatment mass, and so an investigation into medicine masses which did not breach this threshold was carried out.

At SEPA's request, results from the initial medicine mass are not presented graphically in this report, with the focus instead being placed on the applied for medicine mass.

4.2 Mass limit adjustment

Given the limiting nature of the MAC threshold in this specific case, medicine mass was adjusted downwards until results were considered acceptable for this statistic for the proposed treatment scenario. This mass was determined to be 375 g per release, giving an overall limit of 750 g per day. We demonstrate below that:

- 750 g released at a single point in time meets the required 3 hr EQS (giving a 3 hr limit of 750 g);
- 375 g per release (releases at 0, 6, 24, 30, 48, 54, 72 hours from first release) meets the required 72 hr EQS and MAC (giving a 24 hr limit of 750 g).

4.3 3 hr limit – Baseline neap/spring simulations (750 g/pen release)

This section assesses compliance with the 3 hr EQS for baseline pen releases under neap and spring tidal conditions. As noted above, the **3 hr EQS threshold for area over 250 ng l^{-1} concentration, derived using BathAuto, was 0.399 km^2** (Appendix A5).

Timeseries of area above the 3 hr EQS threshold concentration for individual pen releases of 750 g are shown in Figure 4.1, under both neap and spring tide conditions. Times are given relative to the initial release time for each individual pen, aligning timeseries for all pens to a common start point.

Initial trajectories of the areal extent of the plume are similar for the first hour post release, but after this point the area covered shows substantial variability between pens. It is clear from the figure that none of the individual pen releases exceeds the 3 hr EQS, achieving compliance by a large margin in all cases.

In addition to the variation in spatial extent of dispersion, the overall pattern of patch movement from each pen release varies between pens, largely governed by the state of tide at the time of release (Figure 4.2).

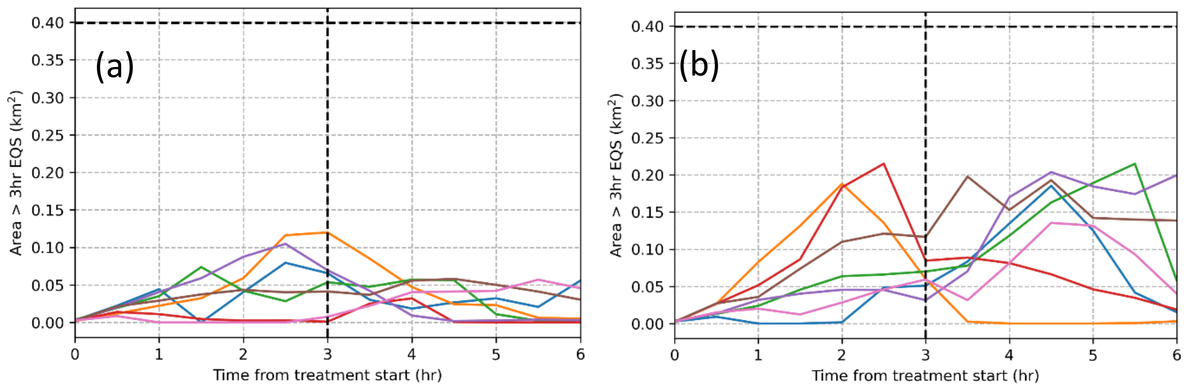

Figure 4.1 Individual pen releases (750 g/pen). Area above the 3 hr EQS concentration threshold (250 ng l^{-1}) for each pen under the baseline (a) neap and (b) spring tide scenarios. Horizontal dotted line indicates the 3 hr ellipse area derived using BathAuto (defining the allowable EQS area). Time is given relative to the time of each pen release, to enable direct comparison of results.

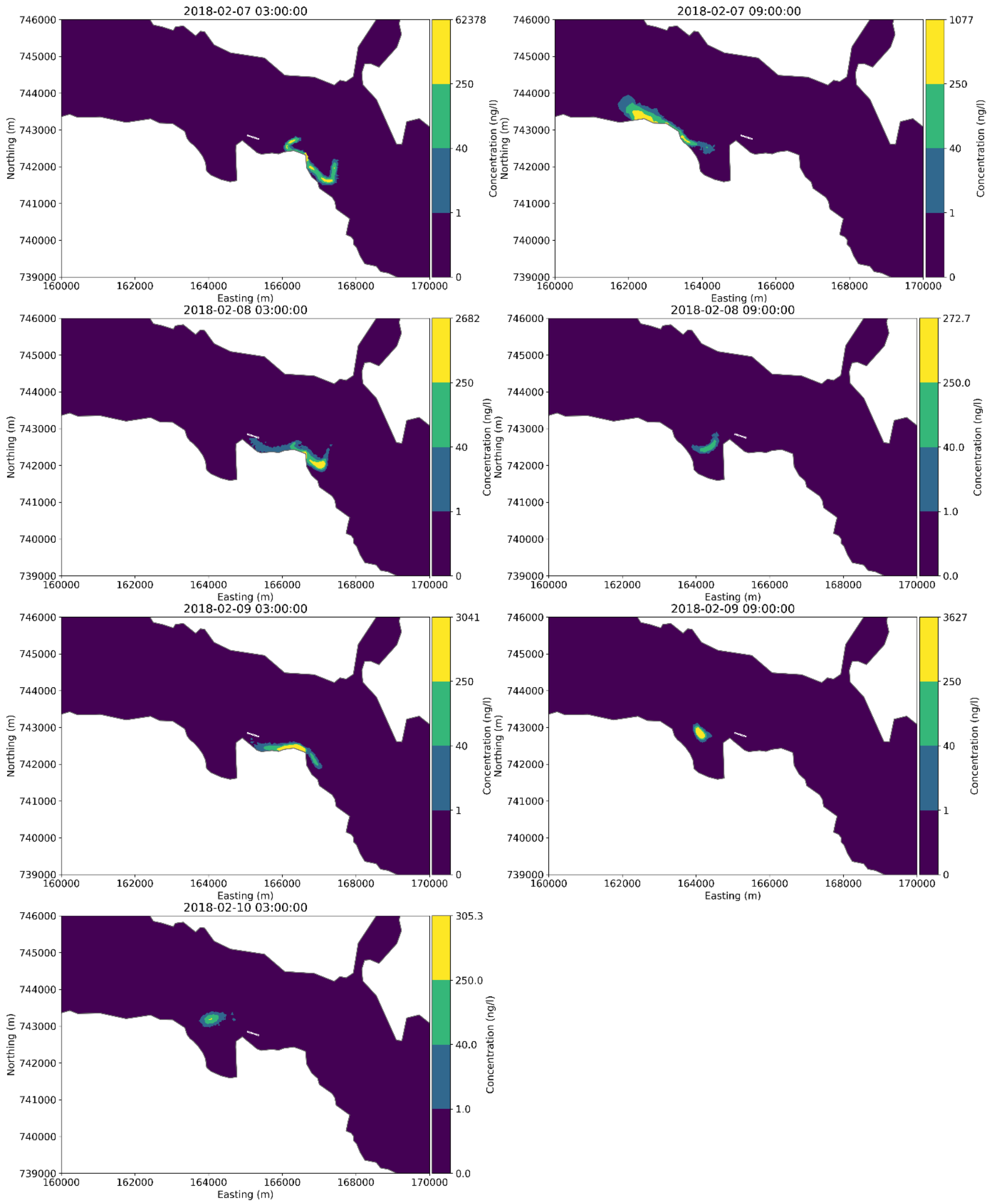

Figure 4.2 Predicted concentration at 3 hrs post release, for individual pen treatments 1-7 (neap tide conditions, plumes from each pen shown in isolation) at 750 g/pen. Contours are shown at EQS concentration thresholds.

4.4 24 hr limit – Baseline neap/spring simulations (375 g/pen release)

This section assesses compliance with the 72 hr MAC and EQS for baseline pen releases under neap and spring tidal conditions. The 72 hr MAC is 100 ng l^{-1}, and the 72 hr EQS threshold for area 40 ng l^{-1} concentration is 0.5 km^2.

In the case of maximum concentration (Figure 4.3), this first falls to the 72 hr MAC within a few hours of final treatment in the neap tide case, and 20 hours in the spring tide case. The peak concentration fluctuates fairly widely, but most values are below the MAC after 10 hours for the neap. Maximum concentration was generally slightly higher under spring tide conditions than under neap (similar to results seen in previous Fishnish A medicine study).

The peaks seen in maximum concentration during the period following completion of treatment generally reflect accumulations of model particles on the coastline. It must be borne in mind that such peaks may simply be artefacts of the model process which are unlikely to be reflected in reality. A more detailed analysis of these artefacts is presented in Section 4.6.

In the case of the EQS 40 ng l^{-1} 72 hr (after final treatment) area threshold of 0.5 km^2 (Figure 4.4), it is clear from the figure that this requirement is easily met. Within around 15 (neap) – 30 (spring) hours of treatment ending, the area above this concentration is generally at or close to zero, excepting occasional small occurrences.

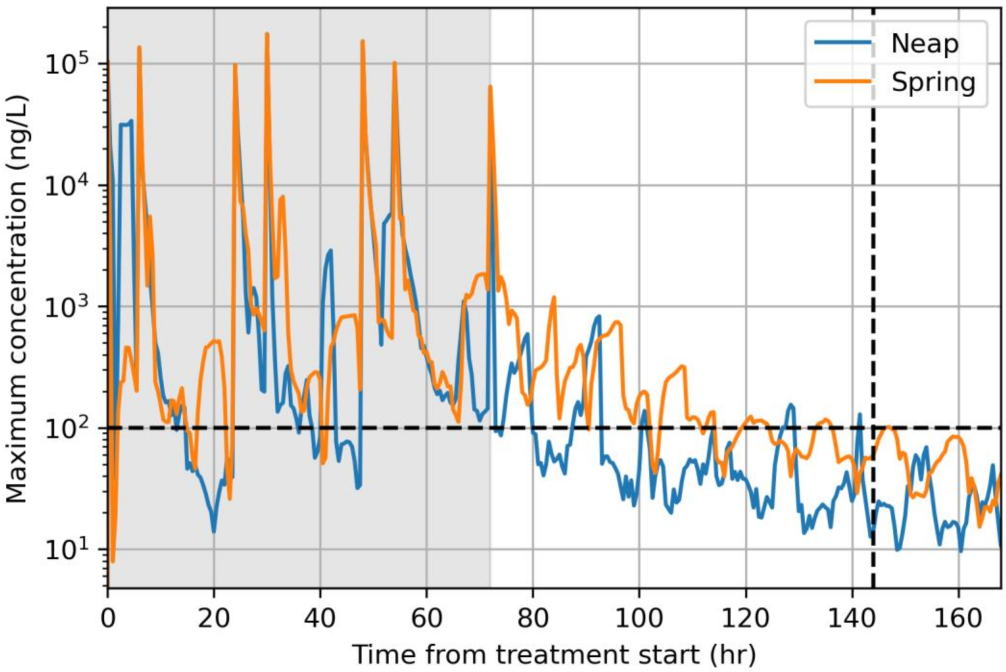

Figure 4.3 Peak concentration for baseline simulations (neap tide: blue; spring tide: orange); 375 g/pen release. Timeseries of predicted maximum concentration within the domain, allowing comparison against MAC (horizontal dashed line) at 72 hrs after the final treatment release (vertical dashed line). Time is given relative to the time of initial release, to enable direct comparison of results.

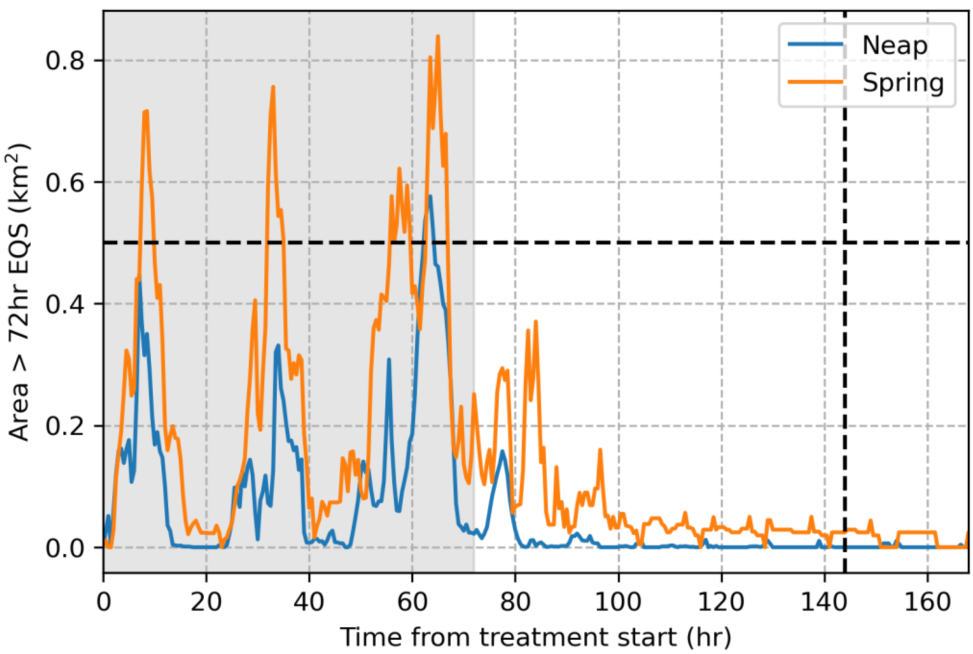

Figure 4.4 Area above 72 hr EQS of 40 ng l[-1] for baseline simulations (neap tide: blue; spring tide: orange); 997.4 g/pen release. Timeseries of predicted area with concentration higher than the 72 hr EQS concentration, allowing comparison with the allowable areal extent of that concentration (horizontal dashed line) at 72 hrs after the final treatment release (vertical dashed line). Time is given relative to the time of initial release, to enable direct comparison of results.

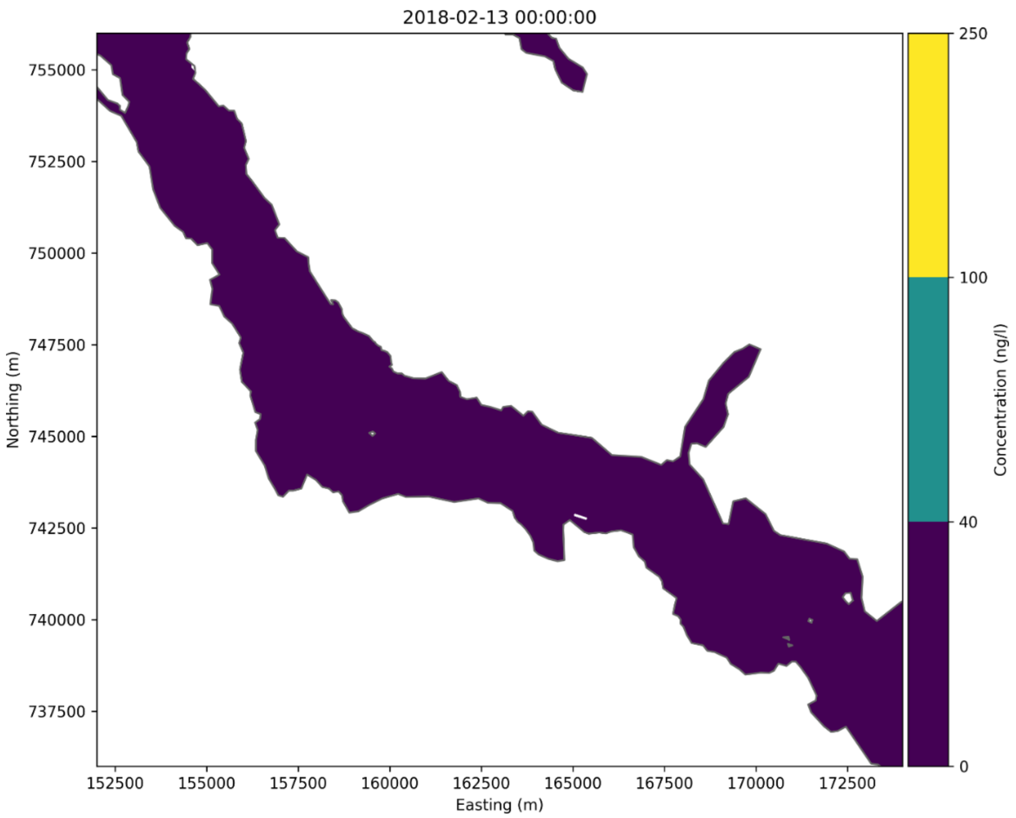

Figure 4.5 Baseline neap simulation predicted concentration at 72 hours after treatment is complete (375 g/pen release). Contours at EQS concentration thresholds (nowhere are these exceeded).

4.5 Sensitivity

4.5.1 Release time

The impacts of adjusting release time by 6 hours before and after the baseline time for neap and spring scenarios are shown in Figure 4.6 and Figure 4.7 respectively.

As in the baseline neap and spring period simulations, the 3 and 72 hr EQS criteria are both easily met in the simulations (panels a, c). The 72 hr MAC threshold is met, excepting a peak for the "neap -6 hr" simulation (see Section 4.6 for detailed breakdown).

Additional plots demonstrating compliance of sensitivity runs with 3 hr EQS for 750 g/pen release (as panel a in Figure 4.6 and Figure 4.7, but with release amount doubled) are shown in Appendix A4, Figures F20-F21.

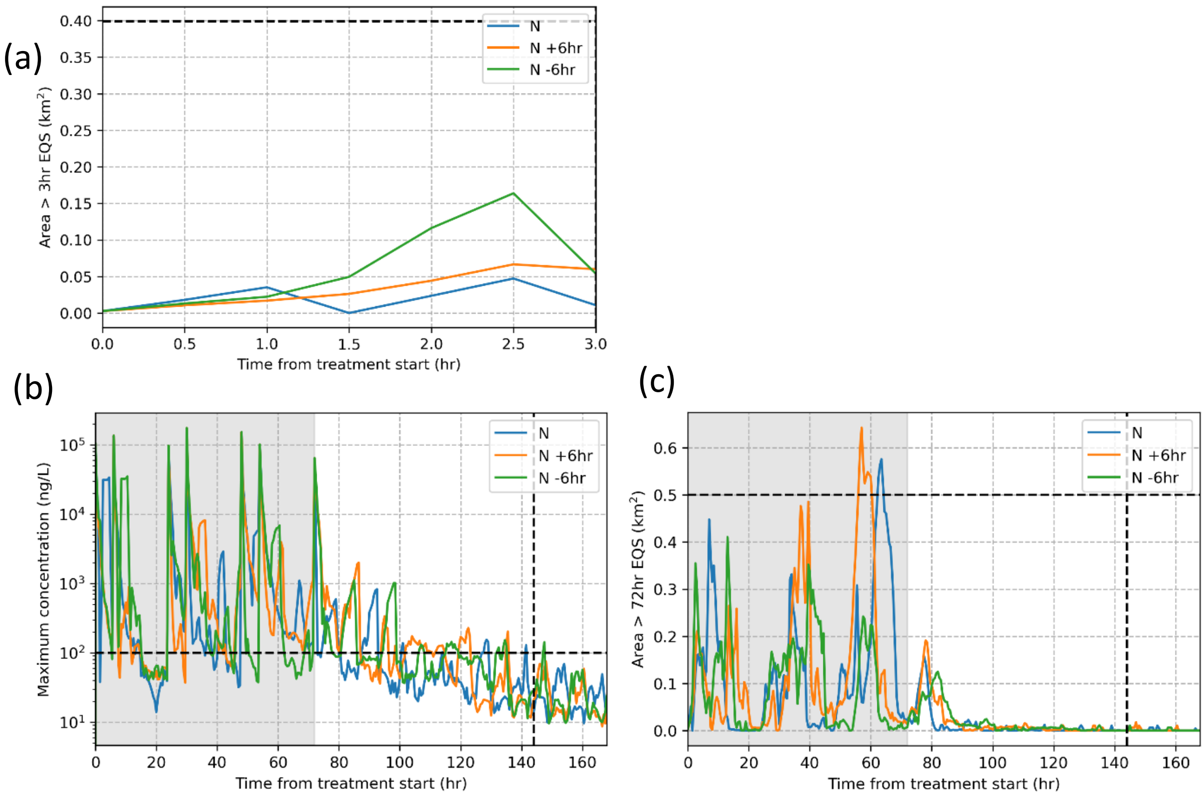

Figure 4.6 Sensitivity to release time for NEAP tide conditions, showing the effect of adjusting release time +/-6 hrs from the baseline time (375 g/pen release). (a) Area of plume with concentration greater than 250 ng l^{-1} (3 hr EQS level), up to 3 hrs, for the first pen treated (6 hr trajectories for all individual pens shown for the baseline case in Figure 4.1a). (b) Maximum concentration anywhere within the domain. (c) Area of plume with concentration greater than 40 ng l^{-1} (72 hr EQS level). Horizontal dashed lines indicate EQS/MAC maximum allowable thresholds, and vertical lines indicate the relevant time for assessment. Time is given relative to the time of initial release, to enable direct comparison of results.

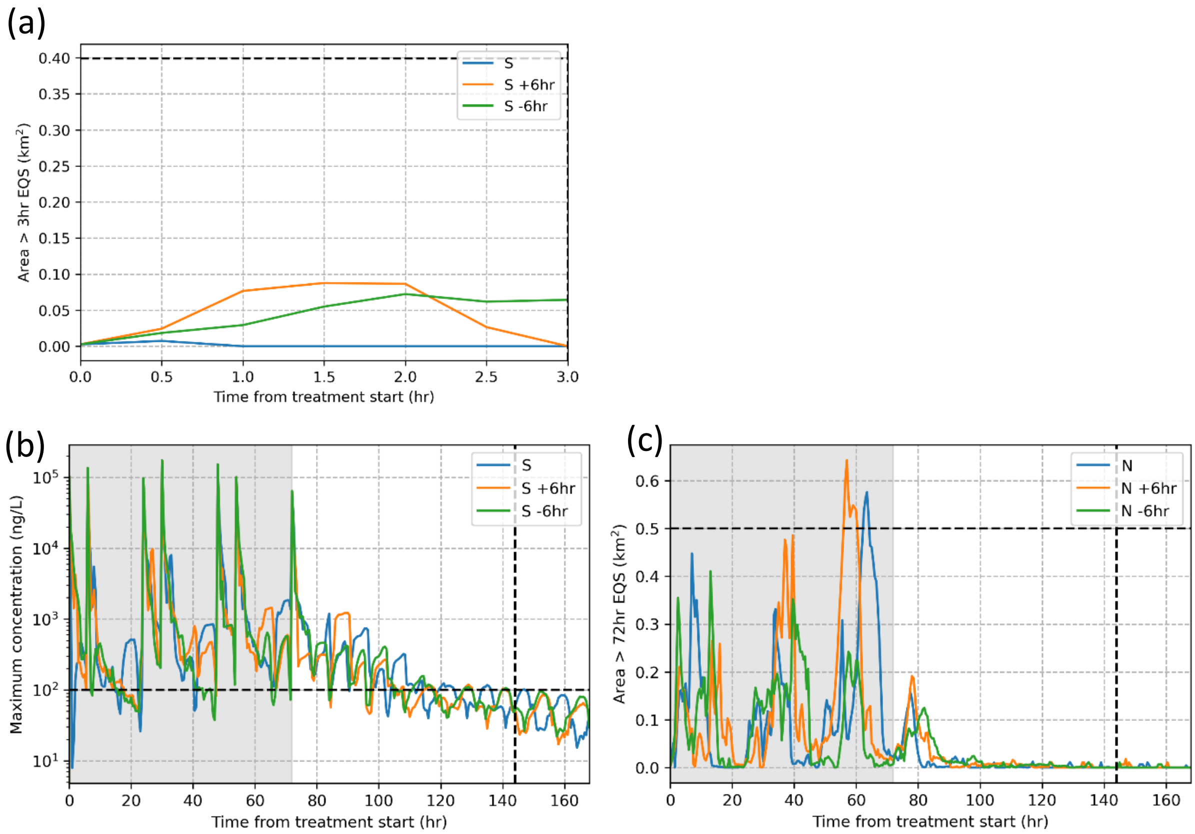

Figure 4.7 Sensitivity to release time for SPRING tide conditions, showing the effect of adjusting release time +/-6 hrs from the baseline time (375 g/pen release). (a) Area of plume with concentration greater than 250 ng l^{-1} (3 hr EQS level), up to 3 hrs, for the first pen treated (6 hr trajectories for all individual pens shown for the baseline case in Figure 4.1b). (b) Maximum concentration anywhere within the domain. (c) Area of plume with concentration greater than 40 ng l^{-1} (72 hr EQS level). Horizontal dashed lines indicate EQS/MAC maximum allowable thresholds, and vertical lines indicate the relevant time for assessment. Time is given relative to the time of initial release, to enable direct comparison of results.

4.5.2 Dispersion coefficient

Results relating to simulations with adjusted diffusion coefficients are shown in Figure 4.8 and Figure 4.9. Empirical observations suggested that the realised diffusion coefficient in the area around the site is likely to be higher than the default value recommended in SEPA guidance (Section 3.4).

Increasing the diffusion coefficient in simulations leads to i) more rapid initial reduction in maximum concentration within the model domain, and ii) greater/faster initial increase in area above a given concentration. The latter effect is particularly noticeable in the area-based metrics. For the later MAC/EQS times the dynamic nature of the local hydrodynamic regime dominates, leading to similar patterns at all parameter values. In all cases the 72 hr EQS criterion is comfortably met. The MAC threshold is also comfortably met in general. However, there is one peak after the determination time for the neap tide higher dispersion simulation, and two longer peaks for the spring tide low dispersion simulation. See Section 4.6 for detailed breakdown.

Additional plots demonstrating compliance of sensitivity runs with 3 hr EQS for 750 g/pen release (as panel a in Figure 4.8 and Figure 4.9, but with release amount doubled) are shown in Appendix A4, Figures F22-F23.

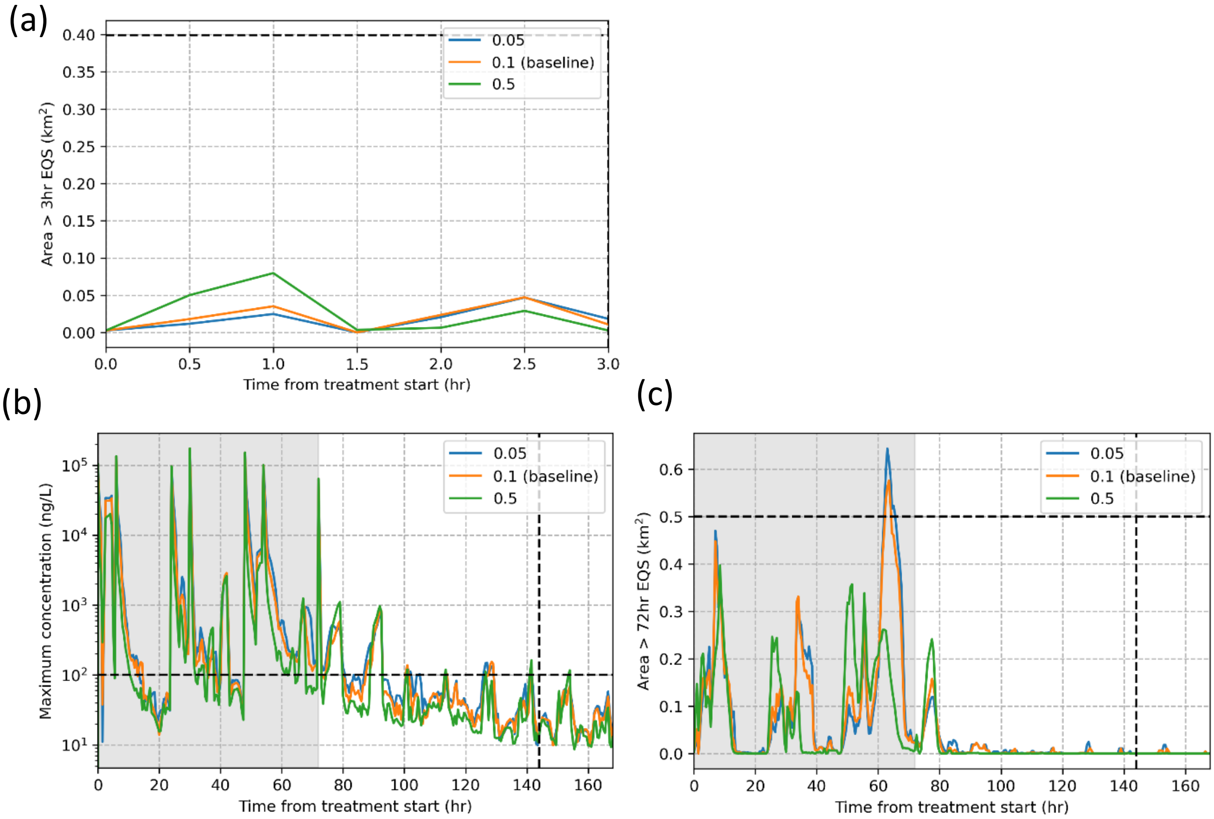

Figure 4.8 Sensitivity to dispersion coefficient, under NEAP tide conditions (375 g/pen release). (a) Area of plume with concentration greater than 250 ng l^{-1} (3 hr EQS level), up to 3 hrs, for the first pen treated. (b) Maximum concentration anywhere within the domain. (c) Area of plume with concentration greater than 40 ng l^{-1} (72 hr EQS level). Horizontal dashed lines indicate EQS/MAC maximum allowable thresholds, and vertical lines indicate the relevant time for assessment.

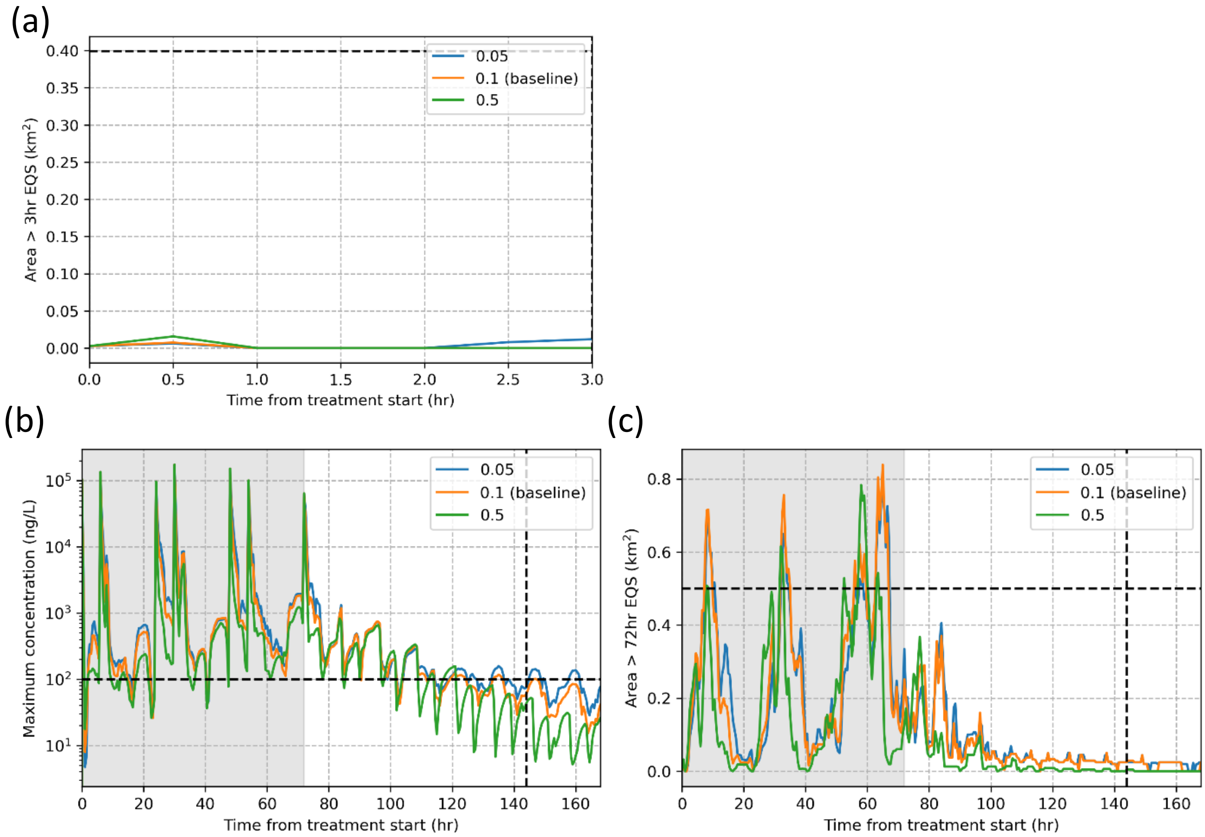

Figure 4.9 Sensitivity to dispersion coefficient, under SPRING tide conditions (375 g/pen release). (a) Area of plume with concentration greater than 250 ng l^{-1} (3 hr EQS level), up to 3 hrs, for the first pen treated. (b) Maximum concentration anywhere within the domain. (c) Area of plume with concentration greater than 40 ng l^{-1} (72 hr EQS level). Horizontal dashed lines indicate EQS/MAC maximum allowable thresholds, and vertical lines indicate the relevant time for assessment.

4.6 Coastal artefacts

Figure 4.10 shows the MAC timeseries plots for all sensitivity runs place on a common axis. All simulations are below the MAC threshold at the 72 hr time point. Three of the simulations have minor peaks above the MAC threshold after this time: momentary for the "neap -6hr" and "neap K_D=0.5 m^2 s^{-1}" cases (the latter of which only just passes the MAC), and more sustained peaks for the "spring K_D=0.05 m^2 s^{-1}" case. Based on the results of the dispersion study, this latter low horizontal dispersion value would almost certainly never be observed in this locality.

Further analysis of the MAC exceedances indicates that there are 10 time point instances of an exceedance across all sensitivity runs. All of these occur at one of two locations (all but one occur in a single model element). The highest exceedance is a value of 134 ng/l. These aggregation locations are on the coastal boundary in a bay and at a headland, and appear to be model artefacts resulting from the numerical methods used for particle transport in the model (see DHI 2015 for numerical method description). While the use of large numbers of particles is expected to adequately reflect the average transport of the dissolved chemicals, such artefacts are not considered to represent reality.

The treatment mass of 375 g (with corresponding 24 hr total of 750 g) is therefore considered to be sufficiently conservative with respect to the MAC.

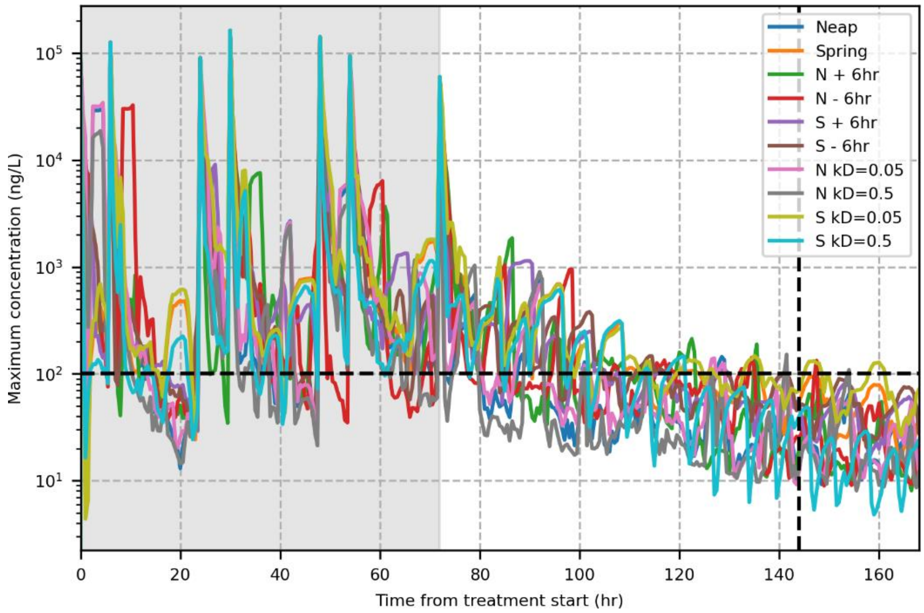

Figure 4.10 72 hr MAC; ensemble of individual pen releases (375 g/release; 750 g/day). Maximum concentration anywhere within the domain. Colours: blue = neap baseline, orange = spring baseline, green = neap+6hr, red = neap-6hr, purple = spring+6hr, brown = spring-6hr, pink = neap baseline with dispersion of 0.05 m^2s^{-1}, grey = neap 0.5 m^2s^{-1}, yellow = spring 0.05 m^2s^{-1}, blue = spring 0.5 m^2s^{-1}. Horizontal dashed line indicates the maximum allowable area, assessment time of 3 hr is indicated by vertical dashed line. Time is given relative to the time of pen release, to enable direct comparison of results.

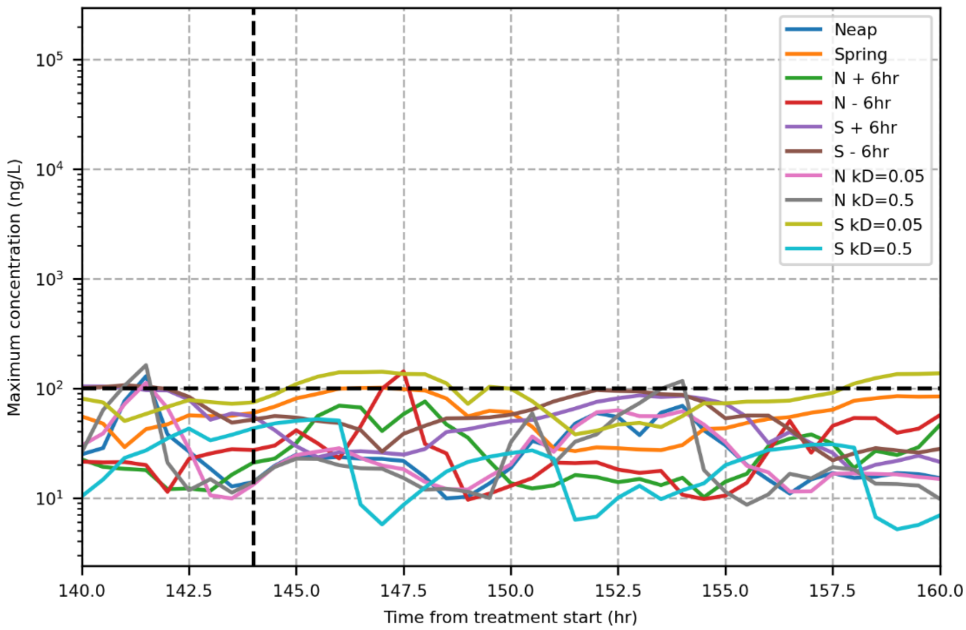

Figure 4.11 72 hr MAC; ensemble of individual pen releases (375 g/release; 750 g/day). Maximum concentration anywhere within the domain. As previous figure but showing results from hours 140-160 only for closer inspection.

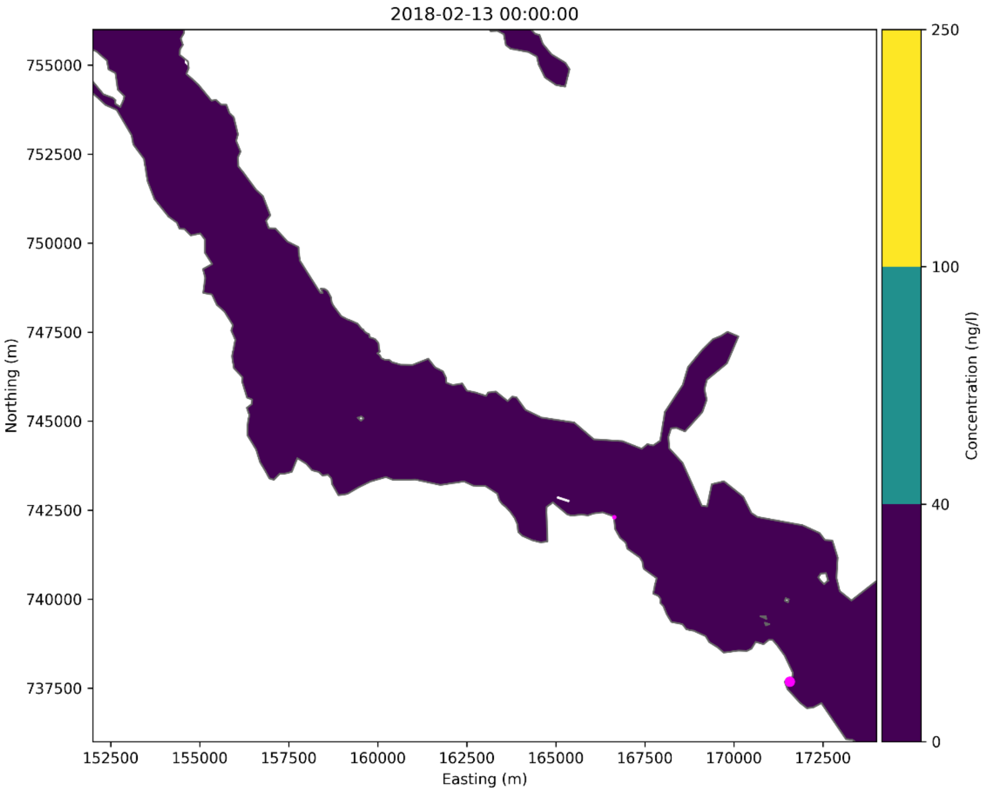

Figure 4.12 Baseline neap simulation predicted concentration at 72 hours after treatment is complete (375 g g/pen release; 750 g/day). Contours at EQS concentration thresholds (nowhere are these exceeded). Magenta points indicate location of MAC exceedances within 24 hr of the assessment time in sensitivity runs (large point = 9 exceedance time points, small point = 1 exceedance time point, over all sensitivity runs).

5 Discussion and Conclusions

The location of the Fishnish B site is at the edge of an open channel with fast and turbulent tidal currents. As such, it is anticipated to be well suited to rapid dispersal of bath medicine residues, as any released materials should be rapidly spread and reduced to levels below those at which any impact might be expected.

The results presented in this document support this hypothesis and indicate that the Fishnish site is expected to be able to support the use of 750 g Azamethiphos bath medicine for a single pen treatment (3 hr EQS test), and 750 g/day (two pens treated at 375 g) for a full site treatment (72 hr MAC and EQS). **The 3 hr and 24 hr limits for Azamethiphos bath medicine should therefore be set at 750 g.**

Sensitivity testing included several different release times as well as adjustments to the horizontal dispersion parameters, in light of an empirical study in the neighbourhood of the site (Anderson 2011). Simulations carried out during sensitivity testing indicated that 3 and 72 hr EQS thresholds could be met comfortably at the applied treatment levels at the original mass tested.

However, at the original 3 hr BathAuto derived medicine mass, exceedance of the MAC limit within a 24 hr window after the 72 hr assessment time was seen in most of the tested scenarios. An investigation of mass adjustment to better meet the MAC criterion was therefore carried out. This determined that – barring some minor peaks at specific coastal locations – a treatment mass of 375 g carried out under the proposed schedule would meet the requirement. Such peaks are demonstrably artefacts relating to the interaction of model particles with the coastline, and therefore not reflective of the behaviour of a dissolved substance such as Azamethiphos.

6 References

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7 Appendices

A1 Hydrodynamic model inputs

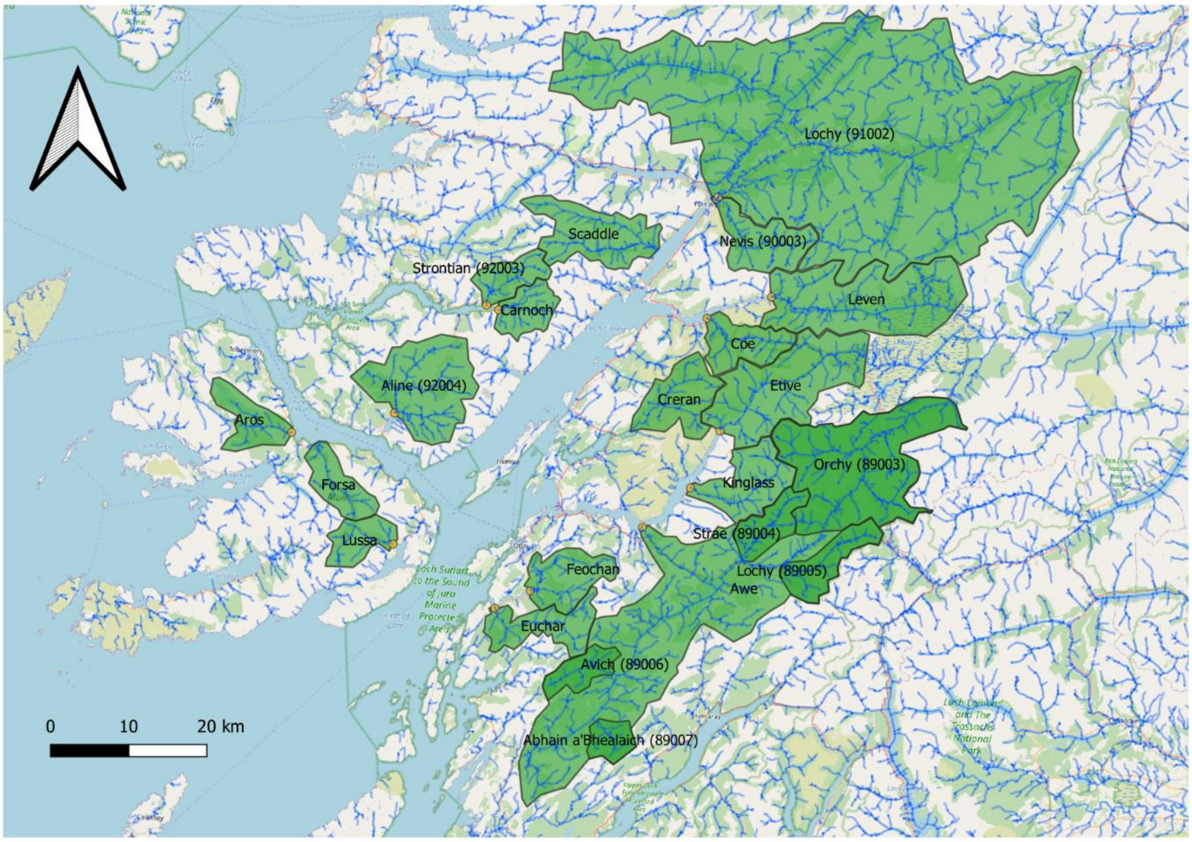

Figure F1 Main river catchments feeding the Loch Linnhe system. CEH reference numbers are given for gauged river catchments, for which daily flow volume data are generally available from 1981-2019.

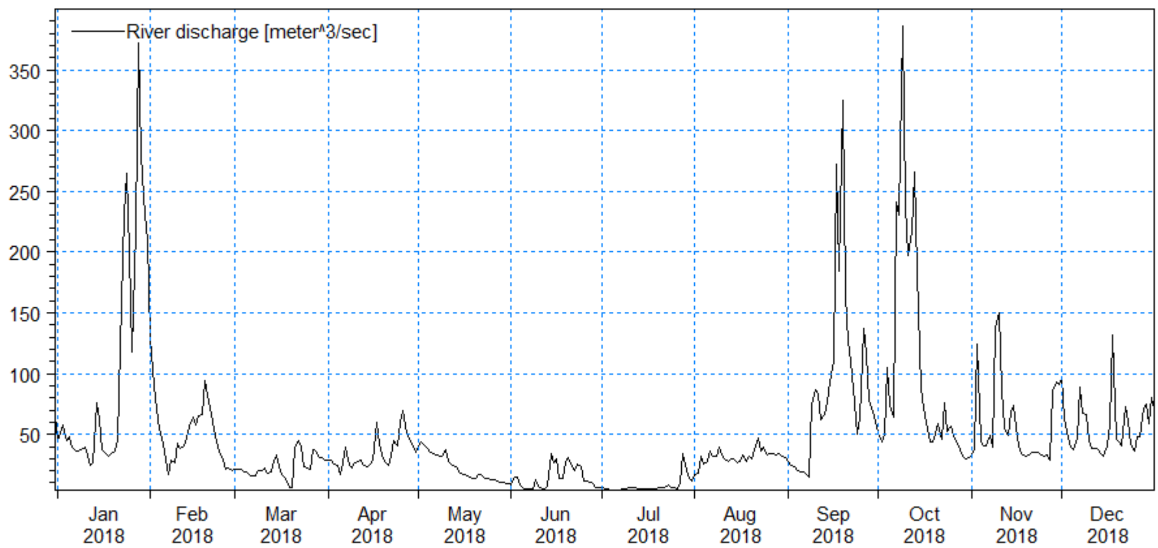

Figure F2 River discharge volume. Discharge from River Lochy (CEH ID 91002; Fort William) over 2018.

Table T1 River catchments feeding the Loch Linnhe domain. 9 of the rivers are gauged; the outflow of the remaining rivers was estimated via a scaling based on the ratio of catchment areas with one of the gauged rivers, multiplied by the provided timeseries.

Name	Easting	Northing	Area (km^2)	CEH_ID	toSea	Scaling	sourceRiver
Abhain a'Bhealaich	195471	707660	26.018	89007	Via Awe	---	---
River Aline	169523	747247	139.238	92004	Yes	---	direct
River Avich	197307	713859	33.935	89006	Via Awe	---	---
River Lochy (2)	219489	727531	52.951	89005	Via Awe	---	---
River Lochy	210963	774945	1347.257	91002	Yes	---	direct
River Nevis	210775	774646	69.845	90003	Yes	---	direct
River Orchy	224348	732239	244.778	89003	Via Awe	---	---
River Strae	214024	728848	43.957	89004	Via Awe	---	---
River Strontian	181305	761059	39.411	92003	Yes	---	direct
Lussa River	169328	730450	39.295		Yes	0.282	Aline_92004
Carnoch River	182869	760454	40.039		Yes	1.016	Strontian_92003
River Forsa	159834	743460	46.62		Yes	0.335	Aline_92004
Aros River	156352	744772	48.383		Yes	0.347	Aline_92004
River Coe	209549	759385	55.436		Yes	0.226	Orchy_89003
River Euchar	182374	722245	62.565		Yes	1.844	Avich_89006
Feochan Rivers	186932	724446	63.938		Yes	1.884	Avich_89006
River Creran	199834	744896	72.51		Yes	0.296	Orchy_89003
River Kinglass	207427	737648	74.544		Yes	1.696	Strae_89004
River Etive	211199	744909	168.817		Yes	0.690	Orchy_89003
River Leven	217816	762104	197.903		Yes	0.808	Orchy_89003
River Awe	201266	732587	830.767		Yes	2.068	Orchy+Strae+Lochy_89005+Avich+AbhaBhea

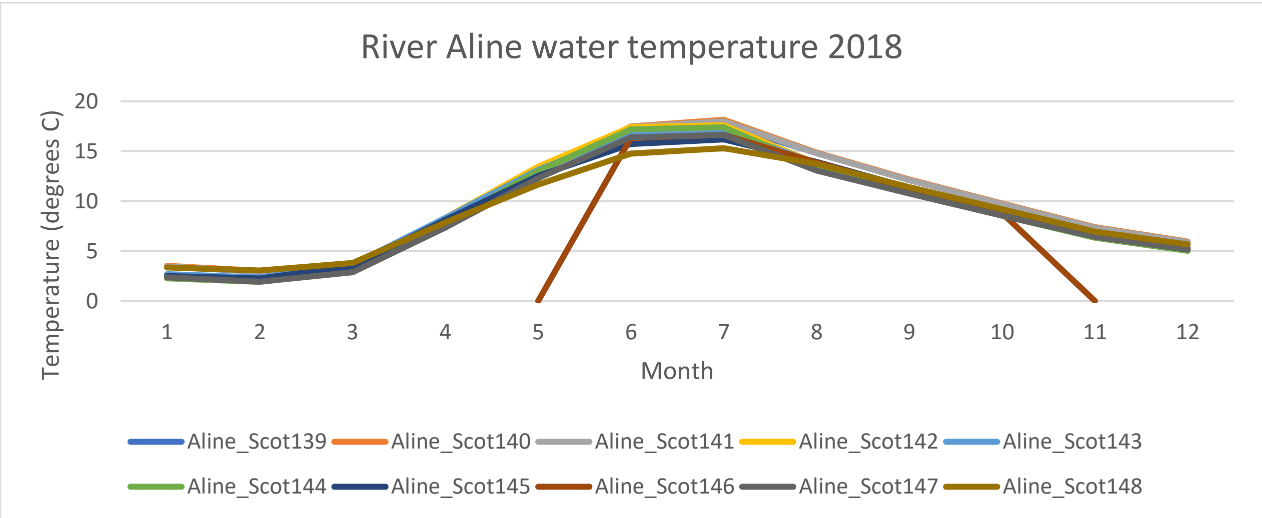

Figure F3 River temperature. Downloaded monthly data from Scottish River Temperature Monitoring Network (https://scotland.shinyapps.io/sg-srtmn-data/) for River Aline (data for station 146 only available June-October).

A2 Hydrodynamic model calibration

A2.1 DPL1Y000: 13/12/2017-12/01/2018 (30 days)

The hydrodynamic model was calibrated against the current meter starting on 13/12/2017 (simulation LL_018). Bottom roughness and wind friction parameters were adjusted over a number of simulations to tune model outputs. The final selected model run used a bottom roughness length of 0.01 m (the measured value) and a wind friction coefficient of 0.01225 (the MIKE default), as no substantial change was found in the match obtained.

Surface elevation was generally matched well by the model, with a mismatch in tidal range seen only for a short period during the neap tide (27/12/2017). Correlation coefficient and Willmott index of agreement (Willmott et al. 2012) were 0.959 and 0.974 respectively, and RMSE was 0.301 m (Figure F4).

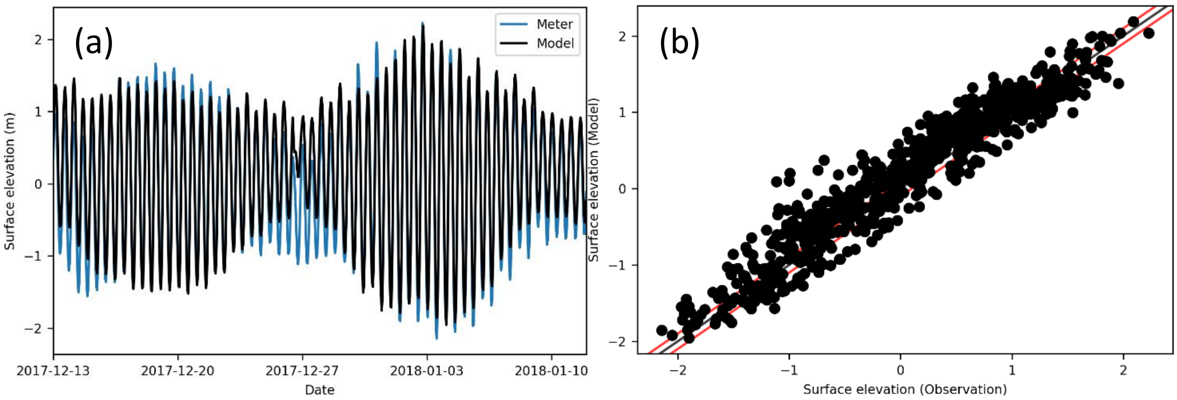

Figure F4 Calibration run 1 (13/12/17-12/01/18). Surface elevation: (a) timeseries showing meter record (blue) and model (black), and (b) scatterplot of model versus meter values (black line indicates perfect match, red lines indicate +/- 0.1 m deviation from this).

Current speeds were well represented by the model at the meter location, with similar distributions of values and comparable maxima. Comparisons were made at 3 depths: sub-surface (-4.0 m), mid-depth (-12.0 m) and near-bed (-26.0 m) (Figure F5). Model extraction depths were adjusted to reflect the local difference between Chart Datum and Mean Sea Level (the latter being used for the model configuration); this being 2.39 m at Tobermory (https://ntslf.org/tides/datum).

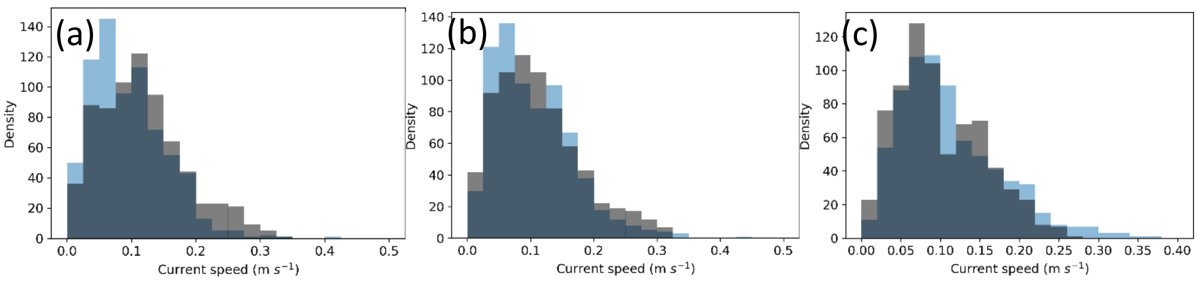

Figure F5 Calibration run 1 (13/12/17-12/01/18). Current speeds: (a) near surface, (b) mid depth, and (c) near bed (meter: blue, model: grey, with darkest areas overlapping).

U and V velocities generated by the model compared quite favourably with observed meter values. Pearson correlation coefficient, Willmott index of agreement (Willmott et al. 2012) and Root Mean Square Error (RMSE) for U and V across depths are summarised in Table T2. In general, a lower correspondence is seen in northward (V) velocity than eastward (U) velocity. This is clear from the less linear pattern of points in the scatter plot of model versus meter (Figure F6d). Current roses (Figure F7) and progressive vector plots (Figure F8) indicate that the difference is reflected in an slight underestimation of southerly current component at all depths. However, due to the location of the site and the shape of the bay, this is not expected to have a large impact on the broader dispersion of medicines.

Table T2 Calibration run 1 (13/12/17-12/01/18). Summary statistics for current velocities. Correlation is Pearson correlation coefficient, and Willmott is the refined index (Willmott et al. 2012). RMSE is de-biased.

	U			**V**		
Depth CD (MSL)	**Correlation**	**Willmott**	**RMSE**	**Correlation**	**Wilmott**	**RMSE**
-4.0 (-6.39)	0.61	0.74	0.083	0.32	0.59	0.062
-12.0 (-14.39)	0.76	0.86	0.068	0.60	0.73	0.055
-26.0 (-28.39)	0.67	0.80	0.071	0.43	0.59	0.084

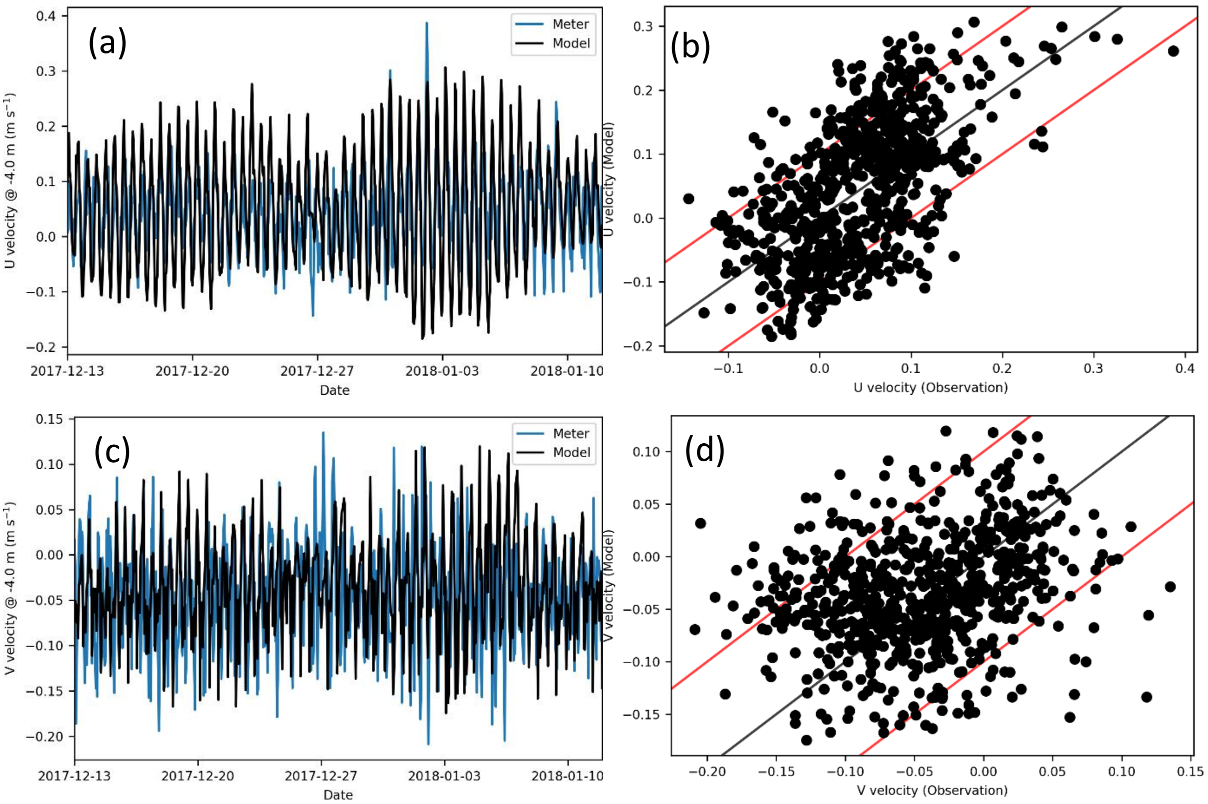

Figure F6 Calibration run 1 (13/12/17-12/01/18). Subsurface velocities: (a) U (eastward) velocity timeseries and (b) scatterplot of model versus meter value. (c,d) As (a,b), but for V (northward) velocity. In b,d, black line indicates perfect match and red lines indicate +/- 0.1 m s^{-1} deviation from this).

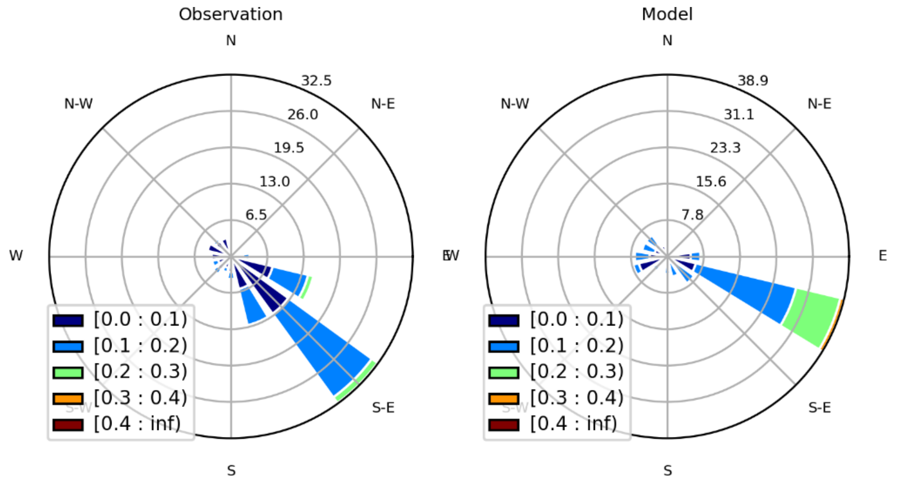

Figure F7 Calibration run 1 (13/12/17-12/01/18). Current roses for sub-surface currents.

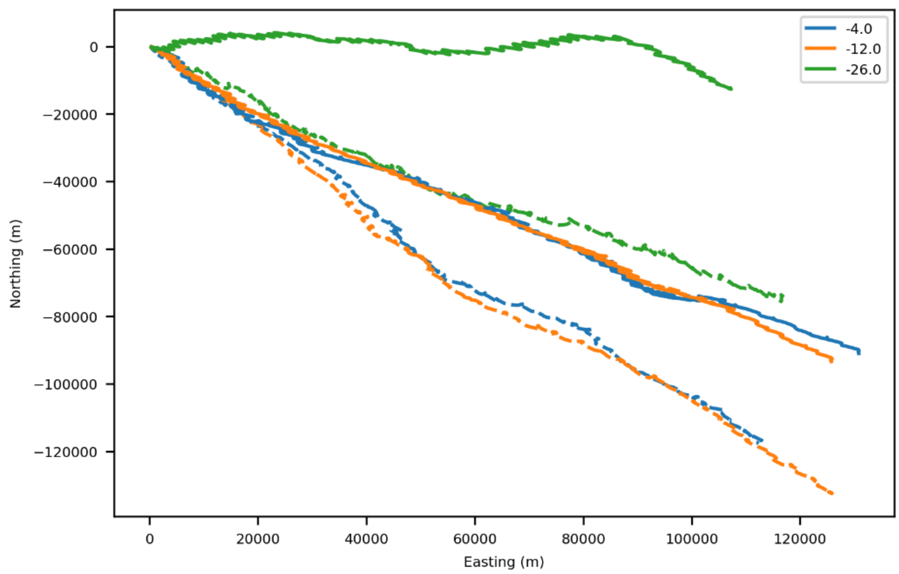

Figure F8 Calibration run 1 (13/12/17-12/01/18). Progressive vector plot showing meter (dashed lines) and model (solid lines) for three depths. Depth in legend is with reference to Chart Datum.

A3 Hydrodynamic model validation

A3.1 DPL1X000: 26/01/2018-13/03/2018 (Fishnish A; 45 days)

The hydrodynamic model was validated against a second current meter record at Fishnish A site starting on 26/01/2018 (simulation LL_017).

Surface elevation was generally matched well by the model, and the match is visually slightly better than the calibration comparison (Figure F9). Correlation coefficient and Willmott index of agreement were 0.97 and 0.98 respectively, and RMSE was 0.284 m.

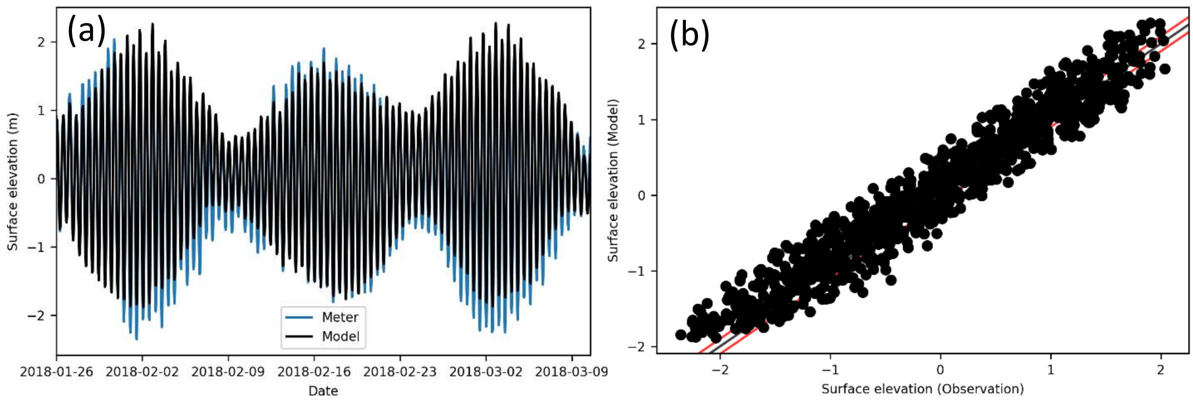

Figure F9 Validation run 1 (Fishnish A; 26/01/18-13/03/18). Surface elevation: (a) timeseries showing meter record (blue) and model (black), and (b) scatterplot of model versus meter values.

For current components, comparisons were made at 3 depths: sub-surface (-4.9 m), mid-depth (-12.9 m) and near-bed (-24.9 m) (model depths adjusted -2.39 m to account for difference between Chart Datum and Mean Sea Level at Tobermory). Current speeds were well represented by the model at the meter location, with similar distributions of values and comparable maxima. However, there is a slight bias towards overestimation of current speed at all three depths (Figure F10).

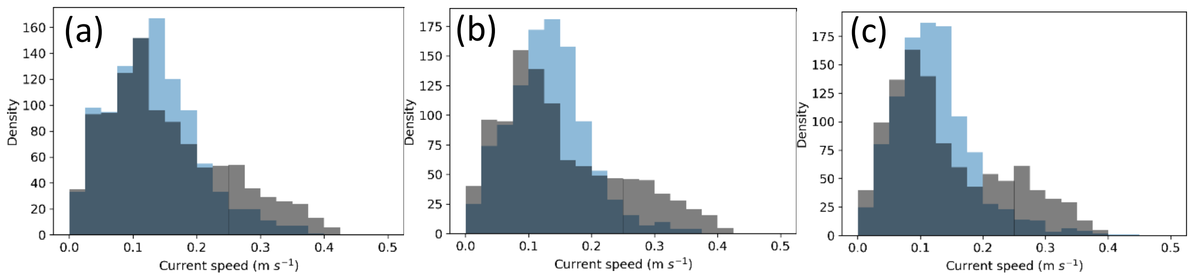

Figure F10 Validation run 1 (Fishnish A; 26/01/18-13/03/18). Current speeds: (a) near surface, (b) mid depth, and (c) near bed (meter: blue, model: black).

U and V velocities generated by the model for this second calibration run compared very favourably with observed meter values. Pearson correlation coefficient, Willmott index of agreement (Willmott et al. 2012) and Root Mean Square Error (RMSE) for U and V across depths are summarised in Table T3. Correlation and Willmot index were consistently higher for velocities over the validation run than they were over the first calibration run, particularly for V velocity (although this remained slightly lower than for U velocity). RMSE was consistently slightly higher than for the first calibration run.

The scatter plot of model versus meter currents (Figure F11d) indicates a good match, but again indicates the slight overestimation of the highest current speeds in the subsurface and near-bed flow (not shown, but reflected in progressive vector plot; Figure F13). Current roses (Figure F12) indicate a match in the dominant current direction (SE). The model here demonstrates an opposing flow at a minority of time points, which is not seen as clearly in the data. However, progressive vector plots (Figure F13) indicate that this does not have a large impact on the predicted cumulative flow, with very similar patterns being seen in overall patterns between meter and model.

Table T3 Validation run 1 (Fishnish A; 26/01/18-13/03/18). statistics for current velocities during the calibration run. Correlation is Pearson correlation coefficient, and Willmott is the refined index (Willmott et al. 2012). RMSE is de-biased.

	U			V		
Depth CD (MSL)	**Correlation**	**Wilmott**	**RMSE**	**Correlation**	**Wilmott**	**RMSE**
-4.9 (-7.29)	0.63	0.77	0.114	0.59	0.76	0.083
-12.9 (-15.29)	0.79	0.87	0.086	0.69	0.82	0.070
-24.9 (-27.29)	0.81	0.87	0.079	0.66	0.81	0.075

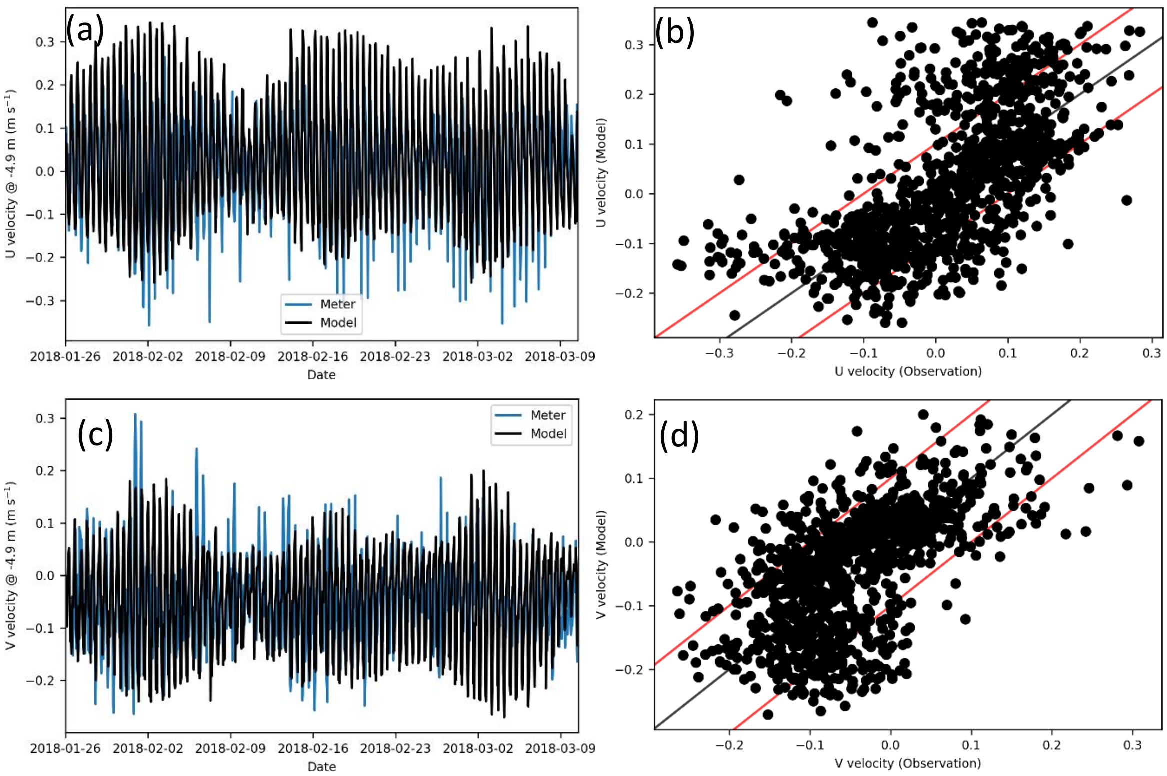

Figure F11 Validation run 1 (Fishnish A; 26/01/18-13/03/18). Subsurface velocities. (a) U (eastward) velocity timeseries and (b) scatterplot of model versus meter value. (c,d) As (a,b), but for V (northward) velocity.

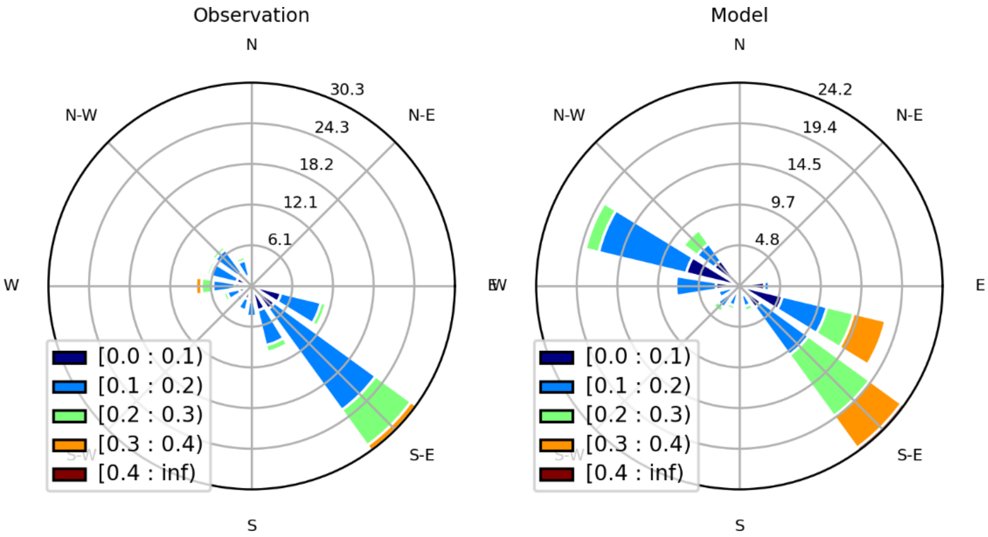

Figure F12 Validation run 1 (Fishnish A; 26/01/18-13/03/18). Current roses for sub-surface currents.

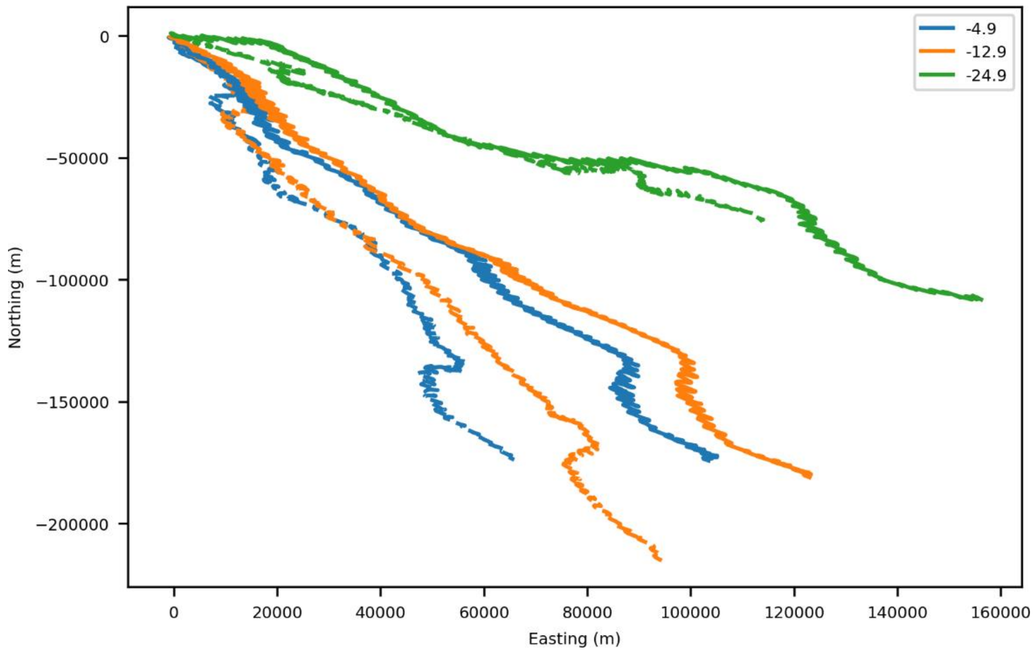

Figure F13 Validation run 1 (Fishnish A; 26/01/18-13/03/18). Progressive vector plot showing meter (dashed lines) and model (solid lines) for three depths.

A3.2 FishB20180126T122904: 26/01/2018-03/03/2018 (Fishnish B; 36 days)

The calibrated hydrodynamic model (using the parameters determined during the calibration runs) was validated against a third current meter record starting on 26/01/2018 and collected at Fishnish B site (the site of interest; simulation LL_018/025).

Surface elevation was generally matched well by the model, and the match is visually slightly better than the calibration comparison (Figure F9). Correlation coefficient and Willmott index of agreement were 0.97 and 0.98 respectively, and RMSE was 0.284 m.

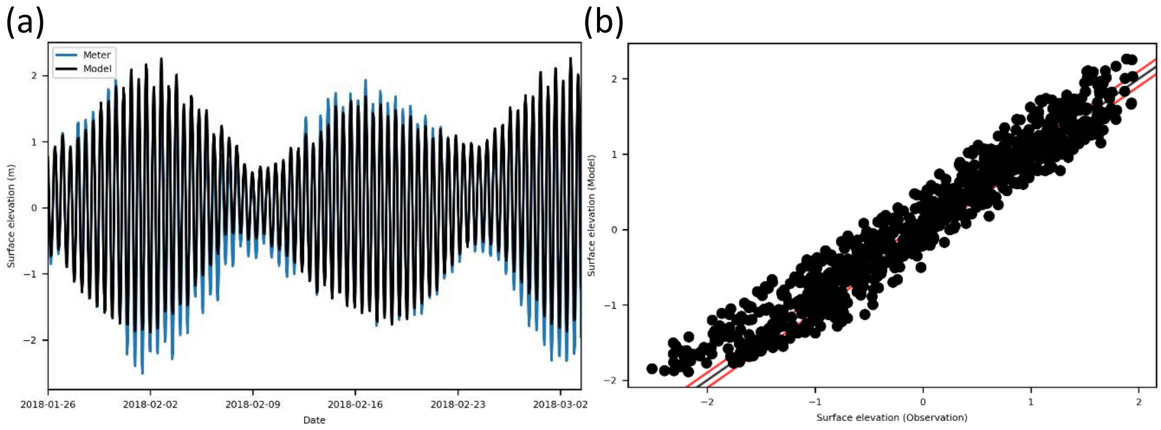

Figure F14 Validation run 2 (Fishnish B; 26/01/18-03/03/18). Surface elevation: (a) timeseries showing meter record (blue) and model (black), and (b) scatterplot of model versus meter values.

For current components, comparisons were made at 3 depths: sub-surface (-7.3 m), mid-depth (-12.3 m) and near-bed (-28.3 m) (model depths adjusted -2.39 m to account for difference between Chart Datum and Mean Sea Level at Tobermory). Current speeds were well represented by the model at the meter location, with similar distributions of values and comparable maxima. Minimal variation was seen over depth, with the meter showing only a slight reduction approaching the seabed (Figure F10).

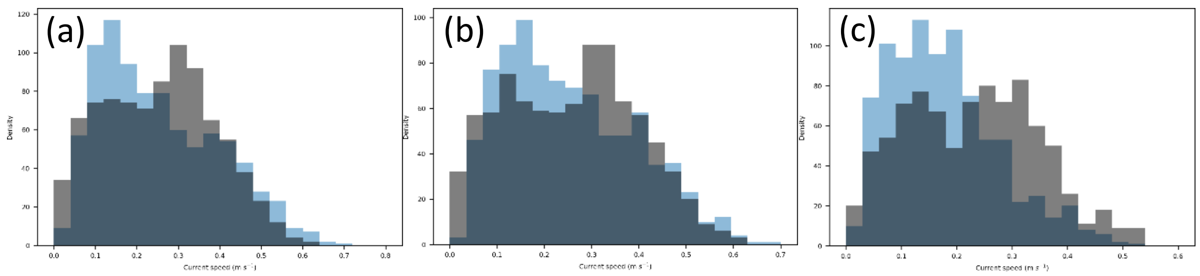

Figure F15 Validation run 2 (Fishnish B; 26/01/18-03/03/18). Current speeds: (a) near surface, (b) mid depth, and (c) near bed (meter: blue, model: black).

U and V velocities generated by the model for the validation run also compared very favourably with observed meter values. Correlation coefficient, Willmott index of agreement and RMSE for U and V across depths are summarised in Table T4. Correlation and Willmot index were consistently higher for U velocity than they were for V velocity at this location. This is reflected in the clearer linear relationship show in the corresponding scatter plots (Figure F11 b,d). RMSE is higher for U velocity than for V velocity, but as a proportion of the mean of absolute values, it is smaller (U velocity is the dominant component of flow at this location).

Current roses (Figure F17) and a scatter plot of current speed and direction (Figure F18) indicate a broad match in the dominant current direction (E/W) and current speed (slightly underestimated for the westerly direction). A slight directional offset can be seen, with observations from the record oriented closer to south than corresponding easterly or westerly dominant flows (Figure F17). The progressive vector plot (Figure F19) indicates this effect very clearly, with observational vectors oriented differently to modelled vectors. However, given the dominance of along-channel flow at the site, and the model's ability to match other features of the flow in close proximity to this location, this is not expected to have an important impact on transport.

Table T4 Validation run 2 (Fishnish B; 26/01/18-03/03/18). statistics for current velocities during the calibration run. Correlation is Pearson correlation coefficient, and Willmott is the refined index (Willmott et al. 2012). RMSE is de-biased.

	U			**V**		
Depth CD (MSL)	**Correlation**	**Wilmott**	**RMSE**	**Correlation**	**Wilmott**	**RMSE**
-4.91 (-7.3)	0.89	0.93	0.133	0.55	0.72	0.068
-9.91 (-12.3)	0.91	0.94	0.120	0.65	0.79	0.058
-25.91 (-28.3)	0.80	0.87	0.144	0.53	0.73	0.073

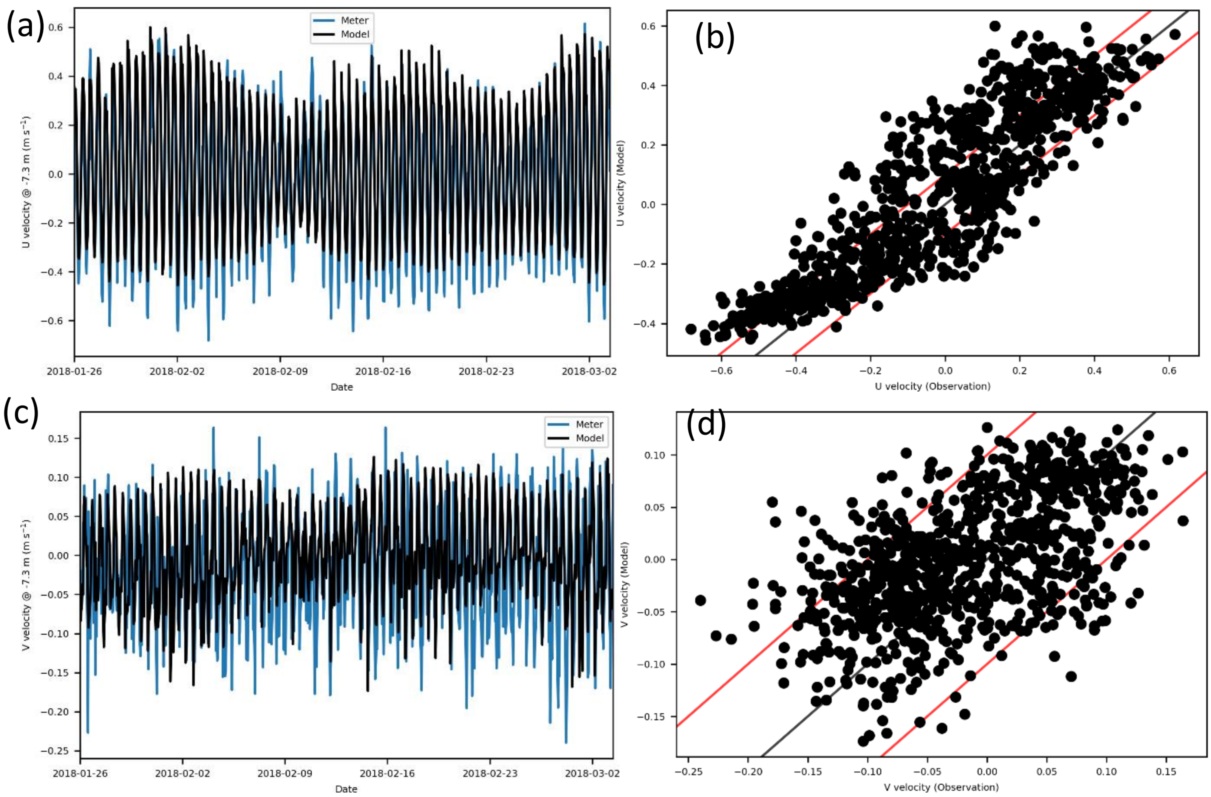

Figure F16 Validation run 2 (Fishnish B; 26/01/18-03/03/18). Subsurface velocities. (a) U (eastward) velocity timeseries and (b) scatterplot of model versus meter value. (c,d) As (a,b), but for V (northward) velocity.

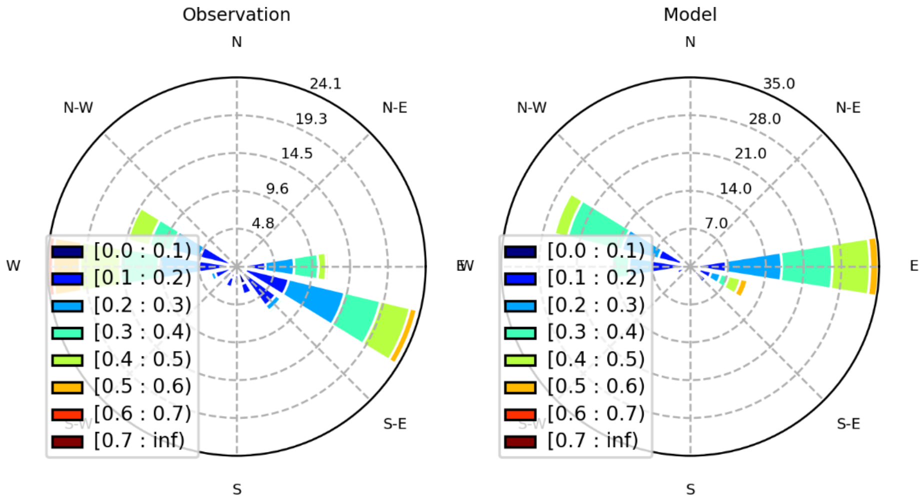

Figure F17 Validation run 2 (Fishnish B; 26/01/18-03/03/18). Current roses for sub-surface currents.

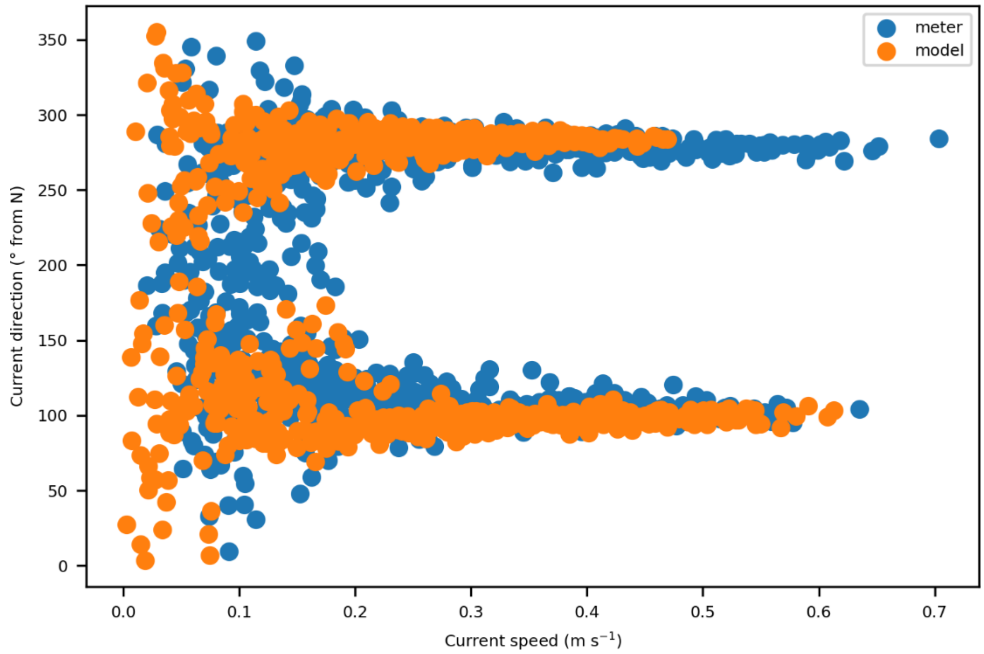

Figure F18 Validation run 2 (Fishnish B; 26/01/18-03/03/18). Current speed and direction for sub-surface currents.

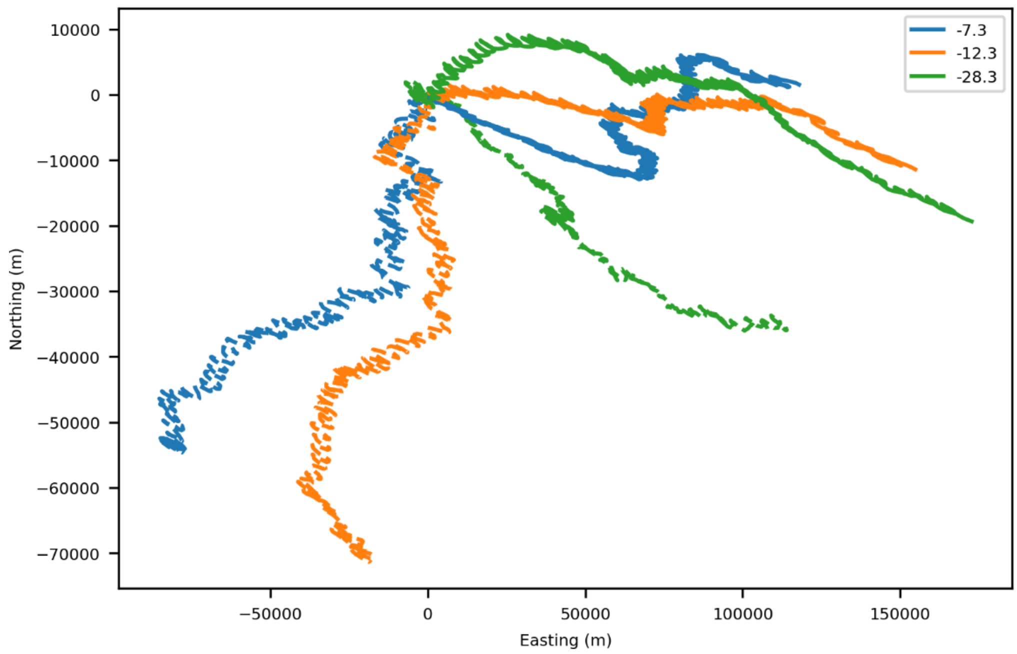

Figure F19 Validation run 2 (Fishnish B; 26/01/18-03/03/18). Progressive vector plot showing meter (dashed lines) and model (solid lines) for three depths.

A4 Additional figures

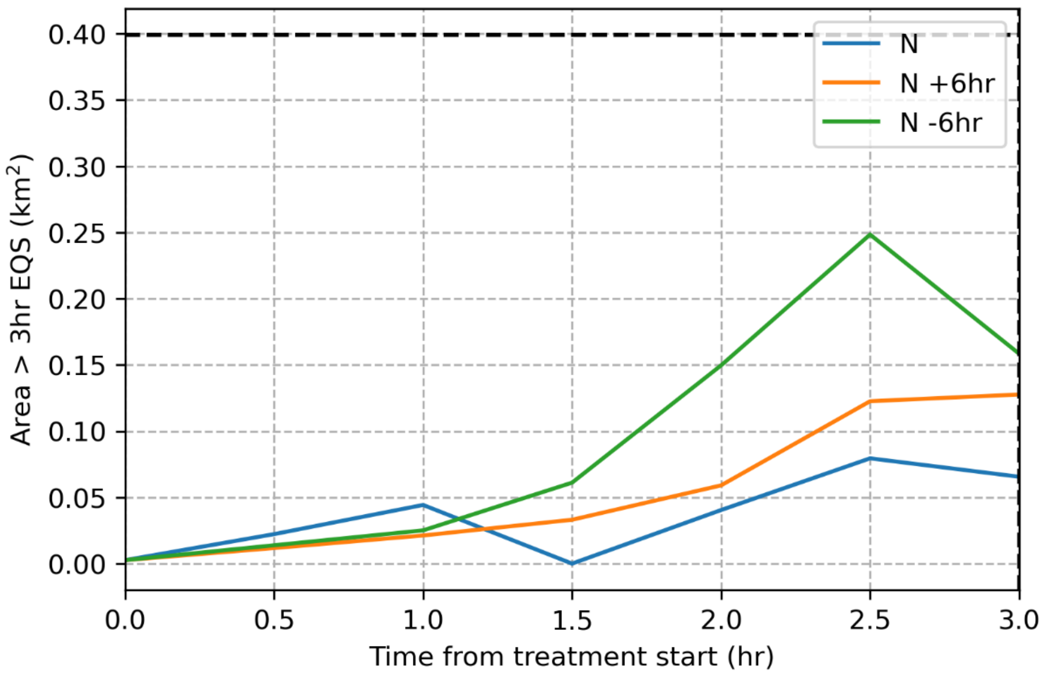

Figure F20 3 hr EQS sensitivity to release time for neap tide simulation (750 g/pen release).

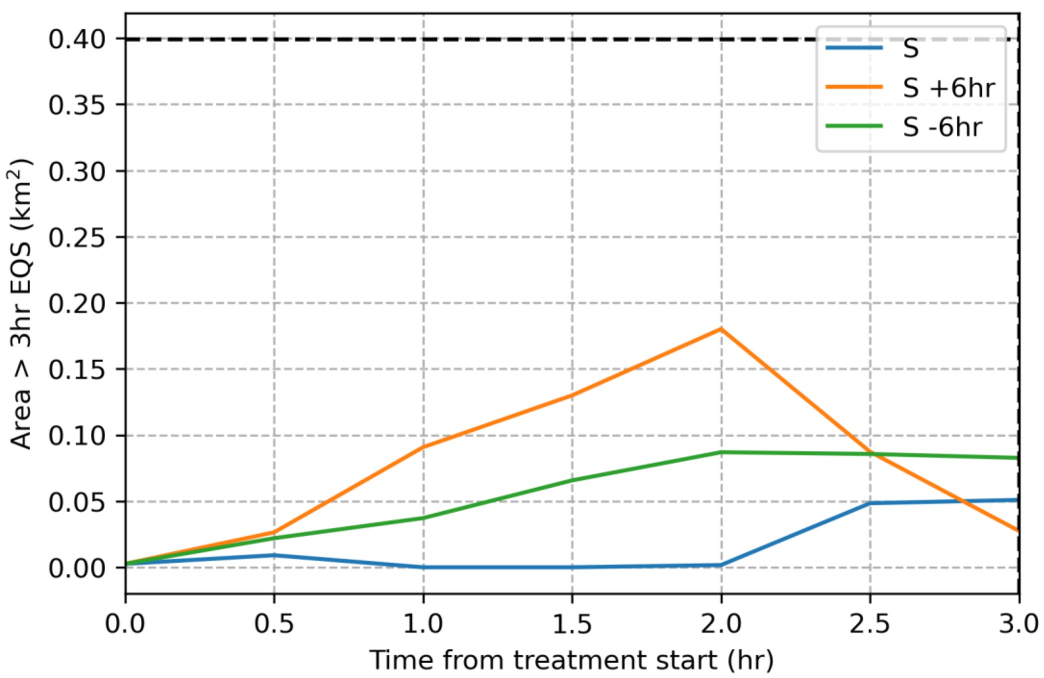

Figure F21 3 hr EQS sensitivity to release time for spring tide simulation (750 g/pen release).

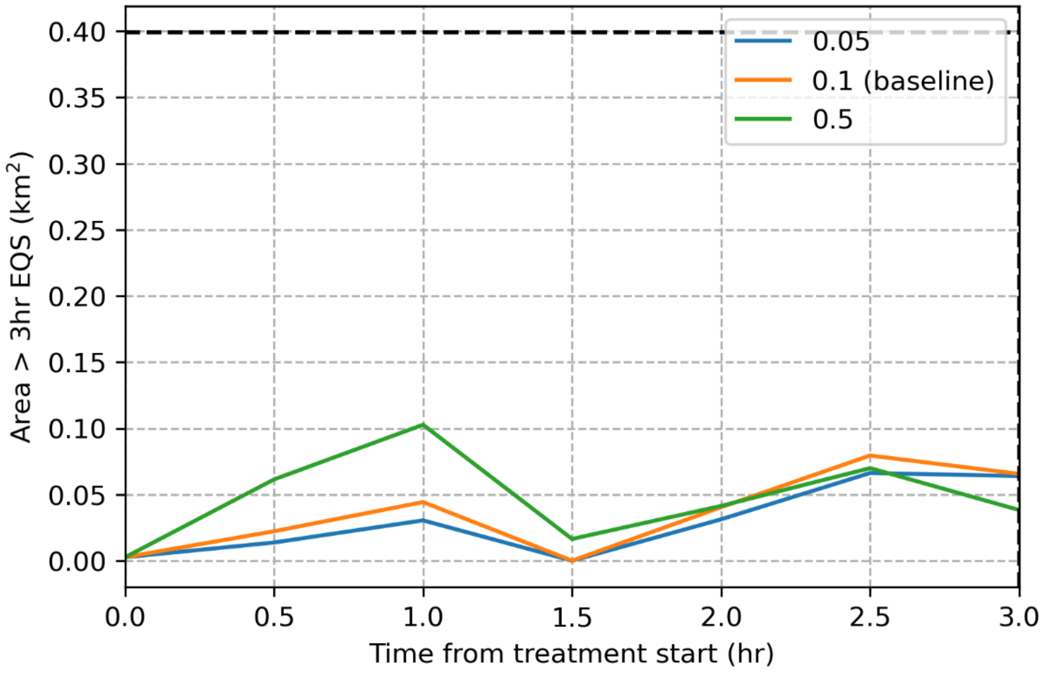

Figure F22 3 hr EQS sensitivity to dispersion coefficient for neap tide simulation (750 g/pen release).

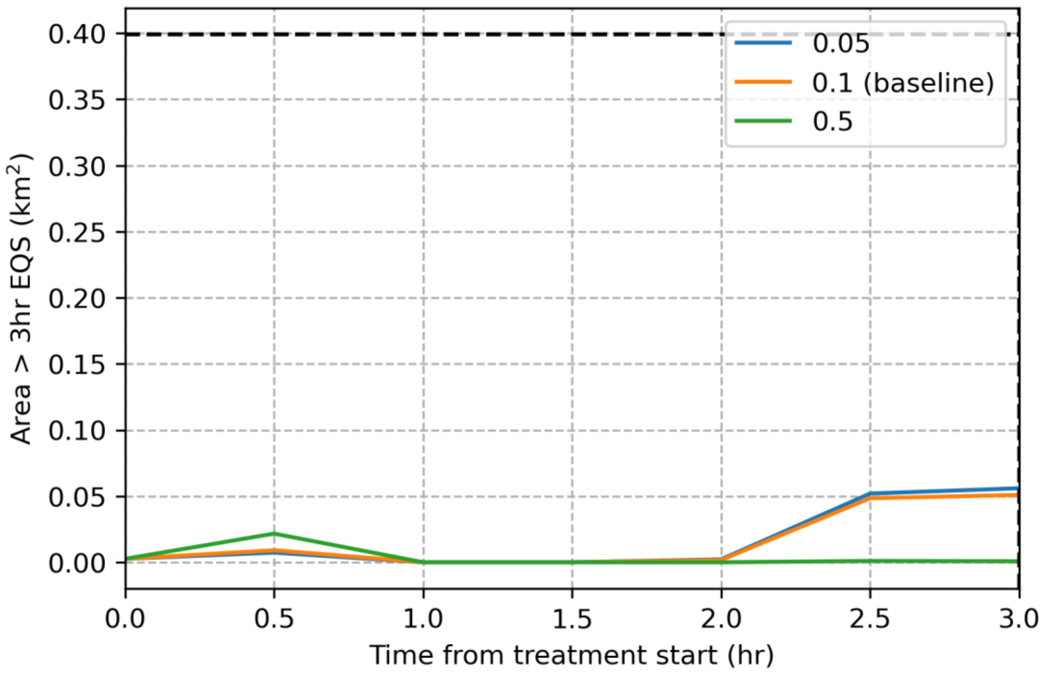

Figure F23 3 hr EQS sensitivity to dispersion coefficient for spring tide simulation (750 g/pen release).

A5 BathAuto calculations

Table T4 BathAuto input used to establish initial 3h starting point.

Site Data	
Site name :	Fishnish B 100 m
Company :	Scottish Sea Farms Limited
Loch Data	
Loch/Strait/Open water :	Strait
Loch area (km^2) :	(only required for **Loch**)
Loch length (km) :	(only required for **Loch**)
Distance to head (km) :	11.34
Distance to shore (km) :	0.26
Width of Strait (km) :	2.18
Average water depth (m) :	31.00
Flushing time (days) :	
Cage Data	
# of cages :	7
Cage shape :	Circle
Diameter/Width (m) :	31.8
Treatment	
No. of cages possible to treat in 3 hours :	6.00
Initial Treatment Depth (m) :	2.0
Treatment Depth Reduction Increment (m) :	0.1
Hydrographic data analysis	
Mean current speed (m/s) :	0.253
Residual Parallel Component U (m/s) :	0.044
Residual Normal Component V (m/s) :	0.003
Tidal Amplitude Parallel Component U (m/s) :	0.400
Tidal Amplitude Normal Component V (m/s) :	0.081

Table T5 Output from BathAuto 3h Azamethiphos calculation.

Mixing Zone depth =	10.00	**m**			
cage depth =	2.0	**m**			
cage width =	31.8	**m**			
cage shape =	Round				
cage volume =	1588.45	**m^3**			
treatment conc'n =	100,000	**ng/l**			
treatment mass =	0.1588	**kg**			
EQS conc'n =	250	**ng/l**	**required dilutions =**	400	

	actual dilutions =	2512

distance from cage to shore	**diffusion coefficient**	**mean current speed**	**Mixing Zone ellipse semi-axis MAJOR**	**Mixing Zone ellipse semi-axis MINOR**	**time**	**Mixing Zone ellipse area**	**treatment volume**	**number of cages that can be treated**	**mean conc'n due to single treatment**	**permitted mass**	**peak conc'n due to single treatment**	**area where conc >EQS**
[m]	**[m^2/s]**	**[m/s]**	**[m]**	**[m]**	**[h]**	**[m^2]**	**[m^3]**		**[ng/l]**	**[g]**	**[ng/l]**	**[km^2]**
255	0.10	0.25	1366	93	3.00 h	3.99E+5	9974	6.3	39.8	997.39	66.4	0.199